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by

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Abstract

A stratified charge engine employing the Texaco Controlled Combustion System has been operated over a large range of load conditions on iso-octane, methanol, and a wide boiling point (100-600°F) residual fuel. Basic performance, emissions and combustion parameters were measured over a range of overall equivalence ratios from ϕ = 0.1 - 1.0 at three engine speeds; 1500, 2000 and 2500 RPM. The basic performance and emissions data were found to vary little between iso-octane and residual fuels, and to compare very well with similar data collected on the same engine design at other research facilities. The engine operation on methanol was not entirely satisfactory due to an improper match between the specific fuel injection system used for these experiments and the design requirements imposed by the much lower heating value and higher stoichiometric fuel-air

mass ratio of methanol.

A direct, online data acquisition system, based on a Digital PDP 11/10 computer was developed to obtain accurate pressure-crankangle data for further combustion and thermodynamic studies. The acquisition program also computes a mean pressure - crankangle diagram and the statistics associated with cycle to cycle variation. The mean pressure - crankangle data is then integrated to compute indicated mean effective pressure. The opportunity to analyze pressure - crankangle data in this way substantially improves the accuracy and speed of data collection.

A simple thermodynamic model based on homogeneous charge engine combustion has been modified to compute the heat release and fuel fraction burnt from the pressure - crankangle data. The problems associated with calculation of these parameters in diesel or stratified charge engines are discussed. Recommendations are made for further development of the online data acquisition system and the thermodynamic model.

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I INTRODUCTION

A stratified charge engine is defined as a spark ignition, internal combustion engine with a non-uniform fuel air mixture in the combustion chamber. Stratified Charge engines have been recognized for good fuel economy potential, low emissions and the ability to burn a wide range of fuel types.(1)* In this thesis, we analyse the performance of an engine based on the Texaco Controlled Combustion System (TCCS).

Several features specific to this design make the engine a strong candidate for small, low power applications. Load control can be achieved by changing the amount of fuel injected and inlet air throttling is unnecessary in most applications. As a result, the engine can be run at very lean overall equivalence ratios giving excellent fuel economy and low emissions. Fuel is injected late in the compression stroke just before the combustion process and is ignited with a spark discharge. The residence time at elevated temperatures is therefore shorter than the time for compression ignition and hence the engine does not display either octane or cetane requirements.

As illustrated schematically in Figure 1, the Texaco Controlled Combustion System uses an open combustion chamber with high air swirl, direct fuel injection and electronic ignition. Air swirl is generated by the inlet air flow, and amplified

*Numbers in parenthesis refer to the bibliography at the end of this paper.

during the compression stroke by constraining the vortex in the combustion chamber. The combustion chamber is essentially a cup with a cylindrical upper section and a toroidal bottom formed in the head of the piston. Fuel is injected with a Roosa Master Pencil Nozzle with a flat seat and a single hole orifice as shown in Figure 2. The positive ignition system uses a high energy multiple spark unit with controlled duration.[2] The spark plug electrodes are carefully aligned to promote the formation of a stable flame front.

High pressure injection of fuel into the swirling air begins near the end of the compression stroke. Air swirl in the combustion chamber promotes mixing and controls the penetration and trajectory of the fuel spray in the cup. The combustible fuel-air mixture formed by turbulent mixing and air entrainment in the fuel jet is then ignited by the long duration spark discharge and burns downstream of the spark plug as shown in Figure 3.

Following B.C. Jain[3] we divide the combustion process into three stages; a rapid combustion phase controlled by the injection rate and a slower "burn up" phase which is controlled by the rate on air entrainment and mixing of burning products and air downstream of the spark plug, and a heat transfer dominated phase which follows after mixing is complete. This sequence is illustrated on the diagram shown in Figure 4. During an isentropic compression or expansion of an ideal gas the value of PV^{γ} remains

constant. After a delay covering the jet transit time for the injector to the flame front, the value of PV^{γ} rises rapidly. This rapid combustion phase appears to be controlled by the injection rate. After the last fuel injected passes the spark plug, the rate of change of PV^{γ} is substantially slower and the rise is controlled by the rate of mixing of the plume of rich products with the surrounding air and residual gas. This phase ends when all mixing is complete or the exhaust valve opens. Any fall in the PV^{γ} curve prior to the exhaust valve opening can be attributed to heat losses.

This research project is a part of a larger program which includes work on a jet mixing model, a performance model and photographic studies with a rapid compression machine.[4] The following areas of research are covered in this thesis;

(1) The completion of the engine test setup and the development of all necessary instrumentation to record the variables of interest.

(2) TCCS engine performance and emissions are presented for the three test fuels over a wide range of operating conditions. Differences in fuel characteristics are also presented.

(3) The problems associated with heat release calculations in stratified charge and diesel engines

reviewed, with the further development of an existing thermodynamic model to predict heat release and mass fraction of fuel burnt outlined.

(4) Log P vs Log V diagrams and plots summarizing the output of the thermodynamic model are presented for a matrix of comparable test data.

(5) The development of computer programs to process raw data and accomplish online pressure data acquisition, along with listings of all computer programs are included as appendixes.

II TEST ENGINE AND INSTRUMENTATION

Single Cylinder Test Engine

The engine used in these experiments is located in the Sloan Automotive Laboratory at MIT, and is arranged as shown in Figure 5. The single cylinder test engine is based on a CFR - 48 crankcase that has been modified to accept a cylinder sleeve assembly, head, piston, crankshaft and overhead cam and valve train assembly for the 3 7/8 inch bore by 3 7/8 inch stroke LIS - 183 TCCS geometry, as shown in Figure 6. Engine specifications and dimensions are shown in Table 1. The engine is coupled to a dynamatic eddy current dynamometer equipped with a hydraulic scale, as shown in Figure 7. The basic instrumentation is listed in Table 3 and whenever possible redundant measurements have been introduced to provide alternate data sources and to qualify experimental results.

The basic engine support facilities were constructed by Lazarewicz(5) and follow standard practices as shown in Figures 8 through 11. The engine cooling system is arranged to enable heat rejection measurements. A rotameter and throttling valve on the return line from the engine allows both flow regulation and measurement while holding system pressure above 5 psig, as shown in Figure 8. Maximum water temperature at the engine cylinder outlet was held at 190 $\pm 5^{o}$F. The lubrication

system shown in Figure 9 consists of two separate loops; a low pressure circulating loop for temperature control and a high pressure bearing feed and filter loop. The operating oil temperature and pressure were held at 165^{o}F and 42 psig respectively. A pressure alarm incorporated in the filter system activates a siren and cuts off the fuel supply and ignition system when pressure falls below 20 psig. Inlet air flow is measured with an ASME square edge orifice with flange taps and water manometers as shown in Figure 10 . Following recommendations made by Lazarewicz, the inlet and exhaust systems were rebuilt and the inlet settling tank and air heater were closely coupled to the engine with a short inlet pipe.

Injection and Ignition Systems:

Fuel system specifications appear in Table 3 and fuel flow is measured gravimetrically as shown in Figure 11 . Transfer pump pressure is held at 25 psig. Fuel injector leakoff and the injector pump bleed are returned to the fuel reservoir mounted on a standard laboratory scale.

Ignition and injection timing, intensity and duration are monitored with a 565 Techtronix Oscilloscope. Ignition timing can be precisely set by a means of a vernier scale and adjustment arm. Injection timing is varied through the use of an American Bosch TMB - 12 Manual Timing mechanism. A pressure transducer

is mounted just ahead of the fuel injector in the high pressure supply line and the Needle Lift Indicator shown in Figure 12 has been developed to replace the standard fuel injector needle lift and cracking pressure adjustment assembly[5]. Both outputs are displayed on the oscilloscope cathode ray tube along with the cylinder pressure crankangle markers and BDC reference pulse as indicated in Figure 13. As presently designed, resolution of fuel injector timing is limited to 2 CA^{o} by the time base necessary to include one entire revolution on the CRT display. The first peak in the pressure trace corresponds to the point of initial needle lift, however; as indicated by the needle lift trace, the injector does not open appreciably for about 2 CA^{o}. Determination of injector cutoff and any secondary injection is only possible with the Needle Lift Indicator. Substantial signal processing problems occur with the linear displacement amplifier and a new design is recommended.

Emission Sampling System:

Engine emissions are measured using the Sloan Laboratory Exhaust Gas Analysis Cart (Table 3). The exhaust sample is removed from an engine exhaust tank consisting of several cylinder volumes and pulled through a heated teflon line and filter to the Gas Analysis Cart. Stainless steel pipe is used between the

engine and exhaust surge tank to reduce the potential for hydrocarbon reactions induced by "rust" and the elevated temperatures of the exhaust flow. An additional spun glass particle filter was installed in the sampling line when it was discovered that at high loads and equivalence ratios near $\phi = 1.0$, the gas analysis equipment was severely contaminated with carbon. This technique appears to have solved this immediate problem.

The development of a computer program to calculate basic engine performance and emissions from the recorded data is described in Appendix I with the complete program listing in Appendix III.

Pressure Volume Measurement:

Accurate combustion pressure and volume measurements are absolutely required for mathematical engine simulation, calculation of heat release rates, engine pumping losses and the compiliation of statistics associated with cyclic variations and peak pressures. Acceptable pressure volume records can only be obtained when the entire monitoring system receives careful attention. First, high resolution signal recording equipment is required if the effort expended to obtain accurate pressure and volume measurements is to be worthwhile. Oscilloscopes were used in these experiments for qualitative analysis but they lack the accuracy required for quantitative resolution. The real time digital computer with analog to digital converters can provide the

resolution necessary; and for these experiments, an online digital data acquisition was developed for Sloan Laboratory PDP 11 Computer Facility. The analog to digital converter provides resolution to within 0.48 psi over a range of 0-1000 psia, well in excess of current engine pressure transducer performance as described in following paragraphs. The sampling intervals were 5 CA^{o}. Appendix II provides details of the system hardware and the development of the software used for online computer sampling. Appendix III contains a listing of the pressure-crankangle data management program and the assembly language program that actually performs the data acquisition.

In these experiments the cylinder head geometry prevented the use of a large diaphragm, water cooled pressure transducer and a Kistler 609A piezoelectric pressure transducer was chosen. Considerable experimental art is required to obtain acceptable performance from available pressure measuring equipment, including this specific unit. For example, quartz piezoelectric transducers are high impedance devices and contamination of the electrical connectors can significantly degrade performance. All connections must be thoroughly cleaned with a freon base solvent and sealed with heat shrink tubing. Transducers are also subject to the thermal cycling that is fundamental to the combustion process in engines. In a chopped flame test by Jain and

Lazarewicz[5], the 609A transducer showed an apparent 6 psi response when directly exposed to an acetylene flame at typical engine frequencies. This response was reduced with a coated diaphragm and a thin coating of silicone rubber was applied as recommended in the literature[6, 7]. The transducer was installed in a recessed adapter inserted through the water jacket of the cylinder head. The adapter cavity is designed to minimize attenuation and protect the transducer from engine temperature fluctuations. The engine coolant also serves to cool the transducer.

Careful preparation of the transducer is wasted if the cylinder volume is not known with similar accuracy. The cylinder volume is computed from engine dimensions and recorded crankangle data. Cylinder clearance volumes were determined by careful measurement of pertinent engine dimensions. The piston top dead center was located and the flywheel position pointer adjusted with a depth micrometer as recommended by Lancaster[7]. A crankshaft driven rotary pulse generator, supplying 720 pulses plus a marker every revolution was then aligned with the flywheel with an accuracy of approximately 1/4 degree. The alignment was tested by analyzing pressure crankangle diagrams and Log P - Log V plots of motoring runs as shown in Figures 14, 15 and 16. Lancaster provides a detailed explanation and interpretation of the plot orientations[7].

A clamped disk balanced pressure indicator was also mounted through the engine water jacket to provide a technique for dynamic calibration for the cylinder pressure transducer. The balance pressure indicator is a pressure activated switch with a reference pressure applied to one side of a thin membrane disk and the cylinder pressure to the other. The balanced pressure indicator is connected to the oscilloscope display as shown in Figure 17 . When the cylinder pressure rises above the reference pressure plus the disk contact pressure, the disk is deflected to ground the center electrode. The change in potential is converted by the cathode ray tube grid modulator to momentary changes in signal intensity on the oscilloscope display as shown in Figure 13 . These pulses are then used to dynamically calibrate the signal from the piezoelectric transducer.

III BASIC PERFORMANCE AND EMISSIONS

The multifuel capability of the TCCS engine was investigated using methanol, iso-octane and a wide boiling point (100-600°F) fuel. Properties of these test fuels are summarized in Table 4. Performance and emissions data in Figures 18 through 39 represents engine operation over the range of fuel-air ratios and engine loads summarized in Table 5. The engine was naturally aspirated and exhausted to ambinet pressure throughout the test series. All performance data was measured with injection timing set for maximum brake torque and ignition system timing set to commence 2 CA$^{\circ}$ prior to the start of injection. The injection duration exceeded the ignition duration of 20 CA$^{\circ}$ except at light load. The overall equivalence ratio was used as the absissa in Figures 18 through 38. The equivalence ratio was determined using two techniques; a) the measured fuel and air flow and b) calculated from the exhaust gas composition using the method of Stivender(8). Data was considered reliable when the difference between these two values was less than 0.025. A deviation greater than this was always traced to operator error, air leaks or faulty equipment. The engine was not operated at fuel air ratios above stoichiometric. Previous experience with this engine has shown that any performance gain above ϕ = 1.0 are achieved with substantially

increased hydrocarbons, CO and degraded fuel economy[5].

<u>Engine Performance with Iso-Octane and Wide Boiling Point Fuel</u>:

The indicated mean effective pressure (IMEP) versus equivalence ratio for iso-octane and the 100-600, wide boiling point fuel are shown in Figures 18 and 19. The maximum IMEP is not developed, with either fuel, in the range of equivalence ratios shown; rather, the effective upper limits for engine operation are determined by a "smoke limit" near $\phi = 1.0$. In addition, there is a distinct flattening of the power curve near stoichiometric conditions. The secondary dependence on RPM exhibited by the IMEP curves can be traced to several factors. The volumetric efficiency increases with speed in the range tested as shown in Figure 39. PV^{γ} plots also show a slight decrease in heat transfer with increasing speed during the heat transfer dominated phase of combustion. As will be discusses in the following chapter, the burning angle appears to decrease slightly with increasing RPM, and this would also serve to increase the IMEP. The data for iso-octane and 100-600 split differently with speed. Similar results have been observed by Texaco[9]. This difference cannot be satisfactorily explained with the basic data comparison presented in this thesis and additional study to resolve this potential conflict is recommended.

The indicated specific fuel consumption (ISFC) is shown for

iso-octane in Figure 20 and for 100-600 in Figure 21. The data sets are of similar character with a clear minimum at an equivalence ratio near $\phi = 0.3$ and a steep rise at leaner equivalence ratios. This rise in ISFC at lean fuel air ratios is accompanied by increased cyclic variations and incomplete combustion; and appears to be a characteristic of the fuel injection system used with this engine.

The indicated thermal efficiency (η_i) provides the best comparison of the actual combustion process since it properly accounts for the different heating values of the three fuels used in these experiments. The indicated thermal efficiency is equal to the reciprocal of the ISFC x lower heating value and the indicated thermal efficiency is equivalent for engine operation on both fuels, with a miximum value of approximately 50% reached near $\phi = 0.3$ as shown in Figures 22 and 23.

The volumetric efficiency (η_v) changes with load to reflect changes in the quantity, composition and state of the residual gas in the combustion chamber as shown in Figures 22 and 23. The effect of engine speed is shown in Figures 22, 23 and 39. The effect of load is shown in brackets on Figure 39.

The exhaust temperature data follows the same trends as described for the IMEP data as shown in Figures 24 and 25.

The friction mean effective pressure (FMEP) versus RPM

for the single cylinder test engine is shown in Figure 39. This data is representative and the actual FMEP showed little variation throughout the test series.

Emissions with Iso-Octane and Wide Boiling Point Fuel:

The TCCS concept is designed to burn the fuel immediately after injection in a fuel rich, mixing controlled plume in order to achieve multifuel capability and low emissions. In the course of these experiments, it was consistently observed that emissions, particularly hydrocarbon and carbon monoxide , are more sensitive to small variations in engine operating conditions than the basic performance data. Careful system timing is required to obtain satisfactory emissions levels and the convention adopted places the start of ignition immediately ahead of injection. However, if timing is adjusted so that fuel injection preceeds ignition higher IMEP levels are achieved with a corresponding significant increase in hydrocarbon emissions at equivalence ratios of $\phi > 0.6$. This system sensitivity is thought to be the source for data scatter at high load conditions and all lines were drawn using a least square regression analysis technique.

The increased cyclic variations and degraded emissions observed at very low load test conditions are thought to be caused by an injection - ignition system phenomena. Two

potential mechanisms for cyclic variations are advanced. High speed movies of TCCS combustion in a Rapid Compression Machine show that the ignition arc discharge time is short compared to the arc cycle time[10]. This ignition characteristic suggests that the initial fuel jet may pass the spark plug in the interval between ignition pulses and a stable flame front may not be formed in the leading edge of the fuel jet. This mechanism introduces the possibility of cycle variation in the initial stages of combustion. At light load conditions the injection duration is less than the ignition duration, and with small injection quantities, the unburnt fuel vapor that passes the electrodes before a stable flame front is formed can rapidly mix to a fuel air ratio below the limit of combustion. This mechanism may partially account for the degradation of hydrocarbon emissions at low load.

A second possible mechanism is traced to fuel injector characteristics. As indicated in Figure 13, needle lift is not always crisp and there is often a 2 CA^{o} period at the start of injection when the needle opens only a small amount. This starting transcient may have substantially influenced the initial stages of fuel jet formation. As shown by Jain, a low momentum jet would be swept outside of the electrode radius by air swirl. The percentage of fuel vapor missing the plug electrodes would increase for light load conditions with the

smaller fuel quantities required. As in the previous case, this phenomenon introduces a mechanism for cycle variation and hydrocarbon and CO formation in the combustion chamber.

Carbon monoxide emissions are shown in Figure 26 for iso-octane and in Figure 27 for 100-600. The lowest CO levels are obtained at an equivalence ratio near $\phi = 0.45$. The CO levels observed with iso-octane are approximately 50% lower than observed with 100-600 at a given equivalence ratio. The mean minimum value observed with iso-octane 4 gr/ihp-hr or 3.5 gr/ihp-hr less than that observed with 100-600.

The hydrocarbon emissions show a sharp increase at equivalence ratios less than $\phi = 0.3$ for both fuels, as seen in Figures 28 and 29. This sharp rise is accompanied by increased cyclic variations which are attributed to the injection and ignition dynamic effects discussed previously. A small rise in HC emissions is also observed near stoichiometric equivalence ratios.

Nitric oxide emissions are shown in Figures 30 and 31. The trends indicated by the data have the same characteristic shape as demonstrated in homogeneous charge spark ignition engines; however, the peak occurs near an overall equivalence ratio of $\phi = 0.6$ whereas in a homogeneous charge engine the measured levels are generally higher and the maximum level occurs near stoichiometric fuel-air ratios.

Methanol Performance and Emissions:

Methanol was chosen as the third test fuel because it represented a severe test of TCCS multifuel capability. The fuel properties of methanol are significantly different from iso-octane or the wide boiling point fuel. Methanol has a much lower specific heating value and a higher stoichiometric air-fuel ratio and thus requires injection quantities nearly twice as large to achieve the same equivalence ratio. A Bosch injection system was used in these tests and the pump and nozzle geometry were selected for the reference fuels. No attempt was made to modify the pump or nozzle for the methanol experiments. As a result, the fuel system was operated off design.

The performance and emissions data for methanol are presented in Figures 32 through 38. Since the fuel system was not optimized for this fuel, wide scatter in emissions data was observed. The basic performance plots in Figures 32 through 35 show the trends to be expected with a properly matched fuel injection system. Figure 32 showing IMEP data exhibits no sensitivity to RPM; however, "misfire" increased with higher RPM at high load conditions. The indicated specific fuel consumption, volumetric efficiency, and thermal efficiency data, as shown in Figures 33 and 34 has trends very similar to the

corresponding trends observed with oso-octane and 100-600 fuel. The indicated thermal efficency (η_i) is almost identical to Figures 22 and 23; the maximum value of approximately 50% occurs at an equivalence ratio near ϕ = 0.3. This demonstrates that the Texaco controlled combustion process is compatible with alcohol fuels; however, fuel system modifications are necessary to properly match the engine with this fuel type.

Comparison of M.I.T. and Texaco Data

The single cylinder engine emissions and performance data compare favorably with the TCCS engine data observed at the Texaco Engine Development Laboratory[9]. The maximum IMEP observed at MIT with 100-600 fuel exceeded the values observed at Texaco by nearly 5% at a given equivalence ratio. The two engines exhibited identical values of volumetric efficiency at each given operating point. Comparative plots by Lazarewicz showed good agreement with all emissions data except hydrocarbon emissions[5]. In these experiments, the level of hydrocarbon emissions observed was considerably reduced when compared to values obtained by Lazarewics; however,the level is still higher than observed at Texaco. This difference in HC levels can be explained by the different sampling techniques used at the two facilities. The Texaco data was acquired in bag samples before analysis, while at the Sloan Laboratory a heated teflon line is used to sample directly from the exhaust tank. The heated

sampling line used at MIT eliminates the potential for condensation of hydrocarbons, and in general, higher hydro carbon levels are measured in experiments with a heated sampling line.

IV ANALYSIS OF PRESSURE VOLUME DATA

Accurate records of cylinder pressure-volume data are an important tool for evaluating performance. The indicated mean effective pressure and pumping mean effective pressure can be computed by integrating the average pressure-volume diagram. In addition, logarithmetic plots of P, V data provide estimates of the combustion delay time, the duration of effective heat release, and the ratio of specific heats, γ, during the isentropic compression and expansion phases. Finally, pressure-volume data is required as an input for the thermodynamic models used to compute heat release and fuel burning rates.

Logarithmetic Pressure Volume Diagrams:

A matrix of comparable test data for engine operation on iso-octane and 100-600 is presented in Table 6 and logarithmetic P-V diagrams are shown in Figures 40 through 57. When pressure-volume data is plotted on a logarithmetic diagram, the isentropic portions of the compression and expansion process appear as straight lines. The slope of the linear segments is equal to (-1) $\cdot\gamma$, where γ is the ratio of specific heats. The beginning and end of combustion are marked by a departure from and return to the straight isentropic compression and expansion lines; since the effect of combustion is equivalent to heat being added

with a consequent change in γ. These points are indicated in Table 6. The apparent burning time for the iso-octane and 100-600 fuels is nearly the same and decreases with increasing RPM. The apparent average burning time is 5.2 ms at 1500 RPM, 3.5 ms at 2000 RPM and 2.7 ms at 2500 RPM. Decreases in engine load only slightly decrease the time required for burning.

The combustion delay time can be determined if the start of injection is known. The injection is tabulated in Table 6 and indicated in each figure. In previous work, this delay has been attributed to the required jet transit time of the fuel from the injector to the stable flame front established at the spark plug electrodes[3]. However, as shown in Table 6 the fuel used also influences the delay time. This indicates droplet evaporation rates may also influence the combustion process. The small dip in the log P log V diagrams during the injection period also indicates the effects of fuel vaporization and this dip is more pronounced when the engine is operated on iso-octane due to its higher latent heat of vaporization.

Heat Release Calculations:

The rate of fuel burning is a basic parameter in most engine models and techniques for calculating fuel burning rates from engine pressure data have received considerable attention. Our understanding of combustion in homogeneous fuel air mixtures

is well developed; however, the increased complexity of heterogeneous charge engine combustion precludes a strictly thermodynamic solution which does not account for mixing in the combustion chamber. This statement applies to both stratified charge and diesel engines and most of the previous work has been done with diesel combustion systems. Until recently, efforts to predict heat release rates in a diesel engine were highly empirical. Lyn has developed relationships to predict heat release rates in an open chamber diesel based on the fuel injection rates[11]. Borman and Kreigher have developed a thermodynamic model to predict burning rates from diesel engine pressure data[12]. In the Borman model, the fuel was assumed to be homogeneously mixed at each time step. This assumption implies very lean equivalence ratios at the start of injection which increase to the overall equivalence ratio. This is physically inconsistent since mixing considerations of the fuel jet imply initially rich combustion followed by progressive mixing down to the final lean overall equivalence ratio. Still other investigations have assumed micro mixtures of burning droplets in which all combustion takes place at stoichiometric considerations[13]. The TCCS performance model developed by Jain assumed that burning took place at equivalence ratios determined by jet mixing and air entrainment and used a specified constant equivalence ratio for the burnt products during its

rapid combustion phase[3]. These assumptions are critical and control the shape of the burning rate diagram computed from pressure-volume data.

The thermodynamic model used in these experiments to predict the cumulative mass of fuel burnt from pressure-volume data is an extension of the two zone homogeneous charge combustion model as outlined below. The closed system is defined as all air, residual gas and fuel vapor in the cylinder prior to ingition. The mass conservation equation can be written as:

$$\bar{v} = v/M = x\bar{v}_b + (1-x)\bar{v}_u \qquad 4.1$$

and the first law as:

$$\bar{e} = (E_o - W - Q)/M = x\bar{e}_b + (1-x)\bar{e}_u \qquad 4.2$$

where

x = charge mass burnt/total charge mass

E_o = total energy of the charge at time t_o

M = the total charge mass, air + fuel + residual gas

Q = the cumulative heat since t_o

v = the combustion chamber volume

W = the work done since t_o

$\bar{e}$ = the average specific energy

$\bar{v}$ = the average specific internal energies

$\bar{e}_b, \bar{e}_v$ = the appropriate average specific volumes

$\bar{v}_b, \bar{v}_u$ = the appropriate average specific internal energies

Subscripts:

b refer to the burnt zone

u refer to the unburnt zone

Further more at a given equivalence ratio ϕ;

$$\bar{v}_u = \bar{v}_u \, (P, T_u) \qquad 4.3$$

$$\bar{v}_b = \bar{v}_b \, (P, T_b) \qquad 4.4$$

$$\bar{e}_u = \bar{e}_u \, (P, T_u) \qquad 4.5$$

$$\bar{e}_b = \bar{e}_b \, (P, T_b) \qquad 4.6$$

where

P = the cylinder pressure

T_u, T_b = the appropriate average zone temperatures.

Assuming the unburnt zone undergoes adiabatic quasistatic compression and expansion, T_u is calculated from;

$$\left(\frac{\partial T}{\partial p}\right)_s = \left[v_u(P_1 T) - \left(\frac{\partial h_u}{\partial p}\right)_T \right] \qquad 4.7$$

Equations 4.1 and 4.2 can be combined to eliminate x, $\bar{T}_b$ is then found by iterative technique. Once $\bar{T}_b$ is known, x, the mass fraction burnt can then be calculated from either 4.1 or 4.2.

This model has been expanded by Martin for use in a heterogeneous charge engine. The burnt zone is considered as burnt products + residual gas uniformly mixed at an externally designated equivalence ratio ϕ_b at each time step. The unburnt zone is divided into two components; unburnt air + residual gas, and the injected but unburnt fuel vapor. Heterogeneous combustion models require a relationship between the fuel fraction burnt and the charge mass burnt since combustion takes place at other than the overall equivalence ratios. The following ratios can be defined:

y = unburnt fuel mass/charge mass

z = fuel mass burnt/total fuel mass

The equation for specific volume and specific energy of the unburnt zones are then written as:

$$\bar{v}_u = (y\bar{v}_{uf} + (1-x-y))\bar{v}_{ua})/(1-x) \qquad 4.8$$

$$\bar{e}_u = (y\bar{e}_{uf} + (1-x-y)\ \bar{e}_{ua})/(1-x) \qquad 4.9$$

Equations for y and z are then expressed in dimensionless ratios.

$$y = \frac{F\bar{\phi}\,(1-R)}{1 + F\phi} - \frac{F\phi_b(1-R)}{1+ RF\bar{\phi} + (1-R)F\phi_6}\,x \qquad 4.10$$

$$z = \frac{\phi_b\;(1+F\bar{\phi})}{\bar{\phi}\;(1+RF\bar{\phi} + (1-R)F\phi_b)}\,x \qquad 4.11$$

where

ϕ_b = the burnt zone equivalence ratio at time t

$\bar{\phi}$ = the average overall equivalence ratio at time t

F = the stoichiometric fuel-air ratio

R = the residual fraction

The computational procedures used to solve for x is the same as in the homogeneous charge model; and z can then be found with Eauation 4.11; however, particular attention must be paid to the change in $\bar{\phi}$ and ϕ_b with time. The overall equivalence ratio only varies during the injection process, and its change is directly related to the fuel injected in each time step. But it will be shown that proper selection of the burnt zone equivalence ratio is not straightforward.

As originally developed by Martin, the modified model assumed a constant unburnt equivalence ratio equal the final overall equivalence ratio and that fuel burned immediately upon injection[4]. Early efforts to use the model in this form with ϕ_b held constant predicted a slow start of combustion prior to

the actual rapid combustion phase, and a final burnt fuel fraction greater than one. The model has been refined by including the variations in unburnt equivalence ratio during injection, and by assuming that the injected but unburnt fuel can be treated as fuel vapor. Procedures for allowing the burnt zone equivalence ratio to change with time have also been included in the computer program.

Sensitivity of the thermodynamic model to ϕ_b is shown in Figure 58. These computations assume no mixing, and the burnt gas equivalence ratio ϕ_b is held constant. The computations are based on pressure-volume data and on overall equivalence ratio of $\bar{\phi}$ = 0.45 at 1500 RPM. Four values of ϕ_b are shown, the overall average equivalence ratio, stoichiometric and two rich mixtures. When burning is assumed to take place at the overall equivalence ratio $\bar{\phi}$ = 0.45, the fuel fraction burnt does not reach 1.0 and the burning time is much larger than predicted by the log P - log V diagram. This homogeneous premixed case is clearly one limiting example. With either rich or stoichiometric burnt gas equivalence ratio, the rapid combustion phase does not significantly vary, however, the curves diverge widely and exceed a value of unity during the mixing controlled combustion. During this period, the mixing rates and burning rates are comparable, by definition,and a mixing model is clearly needed

to account for the change in ϕ_b due to air entrainment by the burning plume if the mass burned is to be correctly related to the physical processes in the engine·

The fuel-air mixtures in the combustion chamber is heterogeneous, and combustion is not limited, a priori to any single equivalence ratio at a given time, the burnt and unburned gases may continually mix throughout the combustion process. As already noted the choice of ϕ_b for each time step during the mixing controlled combustion phase is important and an accurate entrainment model is required. The air entrainment model proposed by Blizard and Keck and developed for the TCCS engine by Jain[3] is used to calculate the mass burned for the same PV data used in the sensitivity study as shown in Figure 59. Entrainment rates predicted by this model were high and the overall equivalence ratio was reached in 15 CA^o, introducing an unrealistic dip in the mass fraction burnt curve. As indicated by the two previous examples, the calculation of burning rates in a stratified charhe engine requires additional development to include mixing before plausible results will be obtained. We postulate that a model developed to predict NO may serve as a tool to aid in untangling the mixing phenomena. The mechanisms of NO formation in homogeneous charge engines are relatively well understood[14]; and the extension of a homogeneous model to

stratified charge engines appears to be plausible.

PV^{γ} Results

An examination of the value of PV^{γ} just before, during and after combustion gives a very good idea of the net heat input or output to the working fluid due to heat release as a result of chemical reaction and/or heat loss[3]. Figure 60 is a plot of PV^{γ} for the same pressure time data as analyzed in Figures 58 and 59. The cylinder pressure and volume at the start of injection is used as the reference (P_oV_o). The values of the specific heat ratio before and after combustion were determined from Figure 41. The solid line represents heat release at constant γ_u while the dashed line represents heat release at γ_b. When the end boundary conditions are applied, namely that the process must start as unburnt and end with its maximum coincident with the burnt maximum, the lines define a very narrow region within which the true heat release curve must fall. The dotted line represents the results of the thermodynamic program discussed in the last section with the burnt products equivalence ratio held at stoichiometric. The rise of this line above the peak value evident in the burnt curve is explained by the rise in the value of fuel mass fraction burnt in Figure 58 to greater than 1.0.

Several conclusions can be drawn from plots of this nature.

The dip in the unburnt curve during the injection period provides further evidence of fuel vaporization, a fact also discussed in the section covering logarithmetic data plots. If the above curves are normalized using the maximum difference in burnt and unburnt curves, a line starting as unburnt and changing to the burnt curve near TDC closely approximates the actual cumulative fuel fraction burnt curve. PV^{γ} plots with γ determined from log P, log V plots can be used to qualify results from a more complete thermodynamic analysis. Note that when normalized PV^{γ} curves are compared to the results of the Figure 58, only the fuel fraction burnt curves in which $0.95 < \phi_b < 1.1$ during the rapid combustion phase fall within the defined boundary region.

The method discussed above can, with careful normalization, provide a very good estimate of cumulative heat release. These estimates can, by comparison with data from detailed thermodynamic, be used to qualify assumptions made in the necessary mixing models.

V CONCLUSIONS AND RECOMMENDATIONS

1. The multifuel capability of the TCCS concept has been demonstrated by tests with iso-octane, a wide boiling point fuel and methanol. The thermal efficiency of the engine is independent of the fuel used. However, proper matching of the fuel injection system is required to achieve satisfactory exhaust emissions levels.

2. The limits on engine operating range are determined by hydrocarbon and CO emissions. The equivalence ratio upper limit is determined by a "smoke limit" near stoichiometric and the lower limit near $\phi = 0.3$ is determined by cyclic variations and high hydrocarbon emissions.

3. Detailed emissions data has been acquired for the three test fuels. Emissions with iso-octane and the wide boiling point fuel exhibit similar trends and compares favorably with previous available data.

4. Further research is required to explain the effects of RPM and different fuel types on indicated mean effective pressure at high load conditions with the TCCS system.

5. Techniques for obtaining online digital data with a small laboratory computer have been demonstrated. The pressure-volume data obtained has been shown to be sufficiently accurate for use in performance models.

6. It has been shown that accurate pressure-volume data can be used to provide a good estimate of cumulative heat release through the use of logarithmetic and PV^{γ} plots.

7. The problems involved in predicting heat release rates have been discussed and the importance of mixing in diesel and stratified charge combustion clearly demonstrated. A detailed thermodynamic analysis of burning rates will require better modelling, both for the mixing of the fuel jet with air before it is entrained in the flame front and for the entrainment of air by the burning plume.

8. It is recommended that a NO_x prediction model be developed for this engine. This model will aid in understanding the role of mixing in stratified charge combustion and can be used to qualify mixing models developed for heat release calculations.

9. Parametric studies involving off design operation are required to explain the sensitivity of hydrocarbon emissions to small variations in injection and ignition phasing.

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APPENDIX I

PERFORMANCE AND EMISSIONS DATA REDUCTION PROGRAM

An interactive data reduction program was written for the Sloan Laboratory PDP 11/10 data analysis facility. The program consists primarily of I/O and is designed specifically for the TCCS engine; however, modifications for other single cylinder engines are possible. All inputs are requested in the same units that are used on the experimental data sheet. Equations used to compute air flow rate in grams/second, coolant flow rate, volumetric efficiency, brake horsepower, and engine emissions require clarification.

Air Flow:

The equation for the flow rate of air through the ASME square edged orifice meter with flange taps is given by the following equation (15).

$$W = 51.94 \; D_2^2 \; KY\sqrt{\frac{P_1}{T_1} \; Gy \; \Delta P}$$

w = mass flow rate grams/second

P_2 = orifice diameter inches

K = flow coefficient

Y = expansion factor

P_1 = static pressure before orifice in in. Hg

T_1 = temperature before orifice ^{o}R

G = specific gravity of gas

y = super compressibility factor

p = pressure drop across orifice in in. H_2O

The computer form of this equation will work with two orifice diameters D_2 = 0.515 and D_2 = 0.71. The program assumes the following variable values:

$$Y = 1 - 7.3 \times 10^{-4} \, \Delta p$$

$$G_{wet} = G_{dry} \left[\frac{1+w}{1+1.608w}\right]$$

$$Y = 1$$

The maximum and minimum Reynolds number can be written as functions of Y and D_2 with N_v = 0.85, RPM Max = 3000 RPM Min = 1000, and inlet air temperature = 90°F

$$Re_{min} = \frac{17174.72}{D_2} \qquad Re_{Max} = \frac{68701.3}{D_2}$$

and appropriate values of K as a function of D_2 determined

$$K = 0.6152 \, D_2^{0.0366}$$

<u>Coolant Flow Rates:</u>

The equation for coolant flow rates was determined by linear regression analysis of calibration data points. 46°F water was used and a density correction was applied to obtain the least squared curve fit given below, good at 175°F.

$\dot{m} = 0.0479\ (h) - 0.0081$

$r = 0.994$

$\dot{m} = \text{lbm/sec}$

h = rotameter height

r = goodness of fit

Volumetric Efficiency:

The engine volumetric efficiency is strictly a function of engine dimensions and operating conditions as shown below:

$$\eta_v = \frac{\dot{m}\left(\frac{2}{N}\right)}{\left(\frac{P_I V}{T_I R}\right)}$$

$\dot{m}$ = air flow rate in lbm/min

N = revolutions/min

P_I = inlet air pressure

V = cylinder volume

R = specific gas constant

T_I = inlet air temperature

after the inclusion of engine geometry and unit conversions

$$\eta_v = \frac{3.\text{TDT}\dot{m}_a (T_I + 460)}{N[0.0193\ P_{atm} - 0.361\ P_I]}$$

Engine Power Output:

The mean effective pressure and horsepower are determined from the following equations (16).

$$hp = \frac{mep\ LAN}{66000}$$

$$hp = \frac{N\Delta h}{K}$$

After including specific engine geometry and an overall dynamometer constant of K = 6000

$$mep = 2.88847\Delta h$$

$$hp = \frac{N\Delta h}{6000}$$

where

A = area of engine piston, $in.^2$

L = stroke, ft.

N = engine RPM

mep = mean effective pressure, psi.

Δh = dynamometer scale height, in Hg.

Specific Emissions:

The average exhaust composition is a function of the equivalence ratio. A model developed by Stivender (8) is used to determine the exhaust based equivalence ratio as a check of the equivalence ratio measured from inlet flow rates; and to compute the engine emissions in grams of pollutant/indicated

horsepower hour. Required inputs are the indicated specific fuel consumption (ISFC), emissions concentrations on a volume basis and the fuel carbon:hydrogen ratio. The model as presented does not apply to alcohol fuels and a method presented by Spindt (17) was used for the methanol experiments.

The model fits one undetermined equilibrium constant for the water-gas reduction to direct measurements:

$$K = \frac{[H_2O]\ [CO]}{[CO_2]\ [H_2]} = 3.8$$

The combustion reaction for a typical hydrocarbon fuel with air may be expressed in the following form:

$$CH_y + (n)\ O_2 + (3.76n)N_2 \rightarrow (a)\ CO_2 + (1\text{-}a\text{-}6c)\ CO +$$

$$+(b)\ H_2O + (c)\ C_6H_{14} + (d)\ NO \rightarrow (y/2\text{-}b\text{-}7c)H_2 +$$

$$(n\text{-}a\text{-}(1\text{-}a\text{-}6c)/2 - b/2 - d/2)\ O_2 + (3.76_n - d/2)N_2$$

The molecular weight of fuel as it appears in the above equation can be written as

$$M_f = 12.01 + 1.008\ y$$

The molecular weight of air is assumed as

$$M_a = 28.96$$

The air fuel ratio can then be written by a carbon and oxygen balance as

$$\frac{A}{F} = 4.76 \frac{M_e}{M_a} [\frac{[CO_2] + [O_2] \frac{[CO] \rightarrow [H_2O] + [NO]}{2}}{[HC] + [CO] + [CO_2]}$$

The HC concentration is measured wet. All other pollutant concentrations are dry and must be corrected by the following relationship

$$[\ ]_{wet} = [\ ]_{dry} (1-[H_2O])$$

An empirical correlation used to determine the exhaust water concentration where the concentrations were wet and K = 3.8, as shown below

$$[H_2O] = \frac{.5y([CO_2] - [CO]}{(\frac{[CO]}{3.8[CO_2]} + 1)}$$

Specific pollutant emissions can be written as

$$\text{IS "X" (gr/ihp-hr)} = \frac{M_x}{M_f} [\frac{[X]_{wet}}{[HC] + [CO] + [CO_2]}] \text{ ISFC}$$

where "X" is the species of interest. When the above equation is used to indicate C_6H_{14} emissions the ["X"] term is [HC]/6 since [HC] is determined by a count of single carbons.

For output consistency fuel consumption is based on the observed air flow and the equivalence ratio calculated from the exhaust products. The computer program listing is included in Appendix III.

APPENDIX II
ONLINE DIGITAL PRESSURE DATA ACQUISITION

Accurate pressure volume data was required and an online digital acquisition system was developed for these experiments. The advantages of direct data acquisition include improved accuracy and speed. With these routines, a large number of data records can be collected and statistically analyzed. Consequently, failure of the experimental techniques can be detected by immediate review and preliminary analysis of the digital data. The online data acquisition system and program described in this appendix is based on a Digital Equipment Company (DEC) 11/10 computer with 16 K of core memory, a DEC RK -05 random access disk, two teletype terminals and the DEC Laboratory Peripheral System (LPS). The DEC LPS consists of an 8 channel multiplexed analog to digital converter with variable gain preamplifiers, and internal timing clock, and two Schmidt triggers. This system has the capability to sample each channel along with its multiplexed pair simultaneously and then perform sequential converstion on the two signals. The sample window length is 5 nano-seconds and each signal conversion takes 25 μS. Maximum sampling rate on a single channel is 45 Hz, with 12 bit conversion.

A schematic of the data acquisition system is shown in Figure 17. The reference marker pulse at the start of the compression

stroke is input to channel 0 with the cylinder pressure input to channel 10. Marker pulses every 5 CA^{o} are used as an input to the Schmidt trigger. It appears that further system refinements will permit 1 CA^{o} sampling increments for a single pair of inputs.

Accurate pressure records must be matched with accurate crankangle records to be of further use and variations in crankshaft angular velocity precludes accurate determination of the cylinder volume when the pressure signal is only logged against time. Consequently, combustion pressure and crankangle position signals make up a data pair and are sychronized with the aid of the Schmidt trigger. Each sample interval consists of 144 data pairs comprising two engine revolutions. The actual crankangle position is not known at the start of a sampling interval and the sampled data is reordered at the end of each data sample interval using a reference signal at 185^{o} before top dead center.

Two techniques can be proposed for obtaining average engine performance. The first involves a complete heat release analysis of individual combustion records followed statistical averaging of these results. The extended interval between sampled data sets and the computational expense required by this method precludes its use. Consequently, a second technique involving the computation of mean cylinder pressure records from consecutive data sets was used. These mean records are then analyzed to obtain engine performance. If a Gaussian distribution

is assumed, the probability density function can be expressed as:

$$\rho(X) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[\frac{-(X_o-\bar{X})^2}{2\sigma^2} \right]$$

The following equations are used to calculate the statistical properties of data variations from N records of data:

$$\text{Mean } (\mu_1) \qquad \bar{X}_i = \frac{1}{N} \sum_{j=i}^{N} X_{ij}$$

$\bar{X}_i$ represents the average value of the i the element of the data vector X.

$$\text{Variance: } (\sigma^2) \quad S_i^2 = \frac{1}{(N-1)} \sum_{j=1}^{N} (X_{ij} - \bar{X}_i)^2$$

Rearranging these equations, the standard deviation can be computed with a single pass of the data:

$$S_i = \sqrt{\frac{1}{N-1}\left[\sum_{j=1}^{N} X_{ij}^2 - \frac{1}{N}\left(\sum_{j=i}^{N} X_{ij} \right)^2 \right]}$$

This routine permits calculation without an unmanageable number of element arrays. However, the standard deviation as calculated is not normalized and can only be expressed as a percent of the

observed element mean.

Assuming that we are sampling from a normal population it is possible to construct exact confidence intervals for μ, the true mean, even when σ is unknown, by use of the Student - t distribution. A 1-α confidence interval for μ_i is expressed as:

$$\bar{X}_i - t_{\alpha/2} \left(\frac{S_i}{\sqrt{N}}\right) < \mu_i < \bar{X}_i + t_{\alpha/2} \left(\frac{S_i}{\sqrt{N}}\right)$$

For a large sample size the distribution of S_i can be closely approximated as normal and a 1- α confidence interval is:

$$\frac{S_i}{1 + \frac{Z_{\alpha/2}}{\sqrt{2N}}} < \sigma_i < \frac{S_i}{1 - \frac{Z_{\alpha/2}}{\sqrt{2N}}}$$

where

$$Z_i = \frac{S_i - \sigma_i}{(\sigma_i/\sqrt{2N})}$$

In addition to the statistical information outlined above, the outline data acquisition program integrates the mean pressure volume diagram to calculate the indicated mean effective pressure and the pumping mean effective pressure by using Simpson's Rule

for non evenly spaced ordinates as shown below:

$$W = \sum_{j=1,3,5..}^{N} [(V_{j+2}(\theta) - V_j(\theta)) (5P_j(\theta) + 8P_{j+1}(\theta) - P_{j+2}(\theta))]$$

Note that cylinder volume is a geometric function of crankangle position.

Log P and Log V vectors are also displayed for cycle evaluation and the program listing containing in stream documentation is included in Appendix III. The assembly language commands for the sampling subprogram are explained in Reference(18).

APPENDIX III

COMPUTER ANALYSIS PROGRAMS

Listings for all computer programs and subroutines used in these experiments are included in this appendix. The programs and subroutines can be grouped in four areas as indicated by Tables A-1 through A-4. All programs contain in-stream documentation of major equations and computational schemes and each subroutine contains a brief section describing its purpose, calling sequence, and the definition and dimensions of arguments. All programs with the exception of subroutine SAMPLE are written in ANS Fortran IV. Subroutine SAMPLE is written in DEC Assembly Language.

Table A-1

Summary of Interactive Data Acquisition and Reduction Programs

Program	Purpose
REZLTS	Calculates basic performance and emissions from experimental data
ONLINE	Performs online pressure data acquisition and calculates mean pressure crankangle statistics
Subroutine	
SAMPLE	Provides assembly language commands used to control analog to digital conversion

Table A-2

Summary of Pressure Crankangle Data
File Preparation and Control Programs

Program	Purpose
ANALIZ	Prepares pressure crankangle data files and basic performance information for additional thermodynamic analysis.
Subroutine	
RECALL	Returns pressure-crankangle data from ONLINE for further calculations.
XPRNT1, XPRNT2	Provides printout of internal variables in XCLC2 for each time increment.
STORE	Provides file storage options for output from ANALIZ.

Table A-3

Summary of TCCS Combustion Analysis Program

Subroutine	Purpose
XCLC2	Calculates fuel fraction burnt, and PV^{γ} versus crankangle from pressure-crankangle data
GASVEL	Calculates the average gas velocities at the periphery of the piston cup*
HEAT2	Calculates heat transfer rate in TCCS engine during combustion
PLUME	Calculates air entrainment rates for burning gas plume**

* Appendix B, Reference (4).

**Appendix II, Reference (3).

Table A-4

Summary of General Thermodynamic Property Subroutines*

Subroutine	Purpose
AFTEMP	Calculates adiabatic flame temperature from given initial state
CLDPRD	Calculates burnt gas properties at low (<1000°K) temperatures
DERIVS	Calculates derivatives of properties; for HPROD
HPROD	Calculates burnt gas properties at temperatures >1100°K
TEMP	Calculates T(h,P) for burnt gas
TSUBU2	Calcualtes T(P) from given initial state of unburnt gas following an isentropic process(assumes no fuel vapor)
UPROPZ	Calculates properties of unburnt gas (assumes no fuel vapor)

*Appendixes C and D; Reference (4)

```
C                       REZLTS
C
C                 THIS PROGRAM WILL REDUCE THE EXPERIMENTAL DATA AS IT IS
C         REQUESTED. ALL INPUTS WILL BE PROMPTED.
C
          DIMENSION T(5), FULFLO(5)
          INTEGER RUN
          REAL MECEFF, NO, IHP, IMEP, ISFC, ITEFF, ISCO, ISNO,NL,ISHC
          DATA DORF/0.71 /
          TYPE 500
500       FORMAT('          THE FOLLOWING INPUTS ARE REQUIRED TO REDUCE THE',
          1' ENGINE DATA')
          TYPE 514
514       FORMAT('          ENTER THE FUEL DATA AS REQUESTED'/' WHAT IS THE ',
          1'H:C RATIO')
          ACCEPT 111,HCR
111       FORMAT(F15.7)
          TYPE 515
515       FORMAT('          WHAT IS THE STOIC FUEL AIR RATIO? ')
          ACCEPT 111, STOIC
          TYPE 516
516       FORMAT('          WHAT IS THE LOWER HEAT OF COMBUSTION? ')
          ACCEPT 111, QC
          TYPE 517
517       FORMAT('          WHAT IS THE FUEL SPECIFIC GRAVITY AT TEST',
          1' TEMP.? ')
          ACCEPT 111, SPGR
          DO 11 I=1, 23
11        TYPE 200
200       FORMAT(/)
          RPML = 100.
1         ACCEPT 5011, NULL
5011      FORMAT(I2)
          TYPE 501
501       FORMAT('          ENTER THE RUN #(I2)    ',$)
```

```
      ACCEPT 100, RUN
100   FORMAT(I2)
      IF ( RUN .EQ. 0 ) GO TO 99
      TYPE 502
502   FORMAT('          THE DATE(A8)    ',$)
      ACCEPT 101, DA,TE
101   FORMAT(A4,A4)
      TYPE 503
503   FORMAT('          THE FUEL USED (A8)    ', $ )
      ACCEPT 101, FU,EL
      TYPE 504
504   FORMAT('          ENTER THE RPM (F5.0)    ', $)
      ACCEPT 111, RPM
      TYPE 505
505   FORMAT('          THE INJECTION START (I3)    ', $)
      ACCEPT 102, INJS
102   FORMAT(I3)
      TYPE 506
506   FORMAT('          THE END OF INJECTION (I2)   ',$)
      ACCEPT 103, INJF
103   FORMAT(I3)
      TYPE 507
507   FORMAT('          THE INJECTOR CRACKING PRESSURE (I4)   ',$)
      ACCEPT 104, INJP
104   FORMAT(I4)
      TYPE 508
508   FORMAT('          THE AMOUNT OF NEEDLE LIFT     ',$)
      ACCEPT 111, NL
      TYPE 509
509   FORMAT('          THE IGNITION START (I3)   ',$)
      ACCEPT 102, IGNS
      TYPE 510
510   FORMAT('          THE END OF IGNITION (I2)   ',$)
      ACCEPT 103, IGNF
      IF ( RPM .EQ. RPML ) GO TO 2
```

```
        K=0
        TYPE 511
511     FORMAT('          WHAT IS THE ATMOSPHERIC PRESSURE IN MM OF HG   ',$)
        ACCEPT 111, PATM
        TYPE 512
512     FORMAT('          HOW MANY GRAINS OF WATER VAPOR ARE',
        1' THERE   ',$)
        ACCEPT 111, WGR
        TYPE 5161
5161    FORMAT(' WHAT IS THE PRESS INTO THE ORIFICE IN IN OF H2O   ',$)
        ACCEPT 111, PINOR
        GO TO 3
2       K = 1
3       RPML = RPM
        TYPE 5171
5171    FORMAT(' WHAT IS THE PRESS DROP ACROSS THE ORIFICE IN IN OF ',
        1'H2O   ',$)
        ACCEPT 111, PDEL
        TYPE 518
518     FORMAT(' WHAT IS THE PRESS DROP IN THE INTAKE MANIFOLD IN IN ',
        1'OF H2O?   ',$)
        ACCEPT 111, PINL
        TYPE 519
519     FORMAT('          WHAT ARE THE DYNO PRESSURES IN INCHES OF HG'/
        1'       FOR BRAKE   ',$)
        ACCEPT 111, PDYB
        TYPE 520
520     FORMAT('          FOR FRICTION   ',$)
        ACCEPT 111, PDYF
        TYPE 521
521     FORMAT('          FOR BRAKE ZERO   ',$)
        ACCEPT 111, PDYBZ
        TYPE 522
522     FORMAT('          FOR FRICTION ZERO   ',$)
        ACCEPT 111, PDYFZ
```

```
      TYPE 523
523   FORMAT('          WHAT ARE THE FOLLOWING TEMPERATURES IN DEG F'/
     1'     WATER IN  ',$)
      ACCEPT 111, TWIN
      TYPE 524
524   FORMAT('          WATER OUT  ',$)
      ACCEPT 111, TWOUT
      TYPE 525
525   FORMAT('          ORIFICE INLET  ',$)
      ACCEPT 111, TORIN
      TYPE 526
526   FORMAT('          INLET MANIFOLD  ',$)
      ACCEPT 111, TAIRIN
      TYPE 527
527   FORMAT('          EXHAUST  ',$)
      ACCEPT 111, TEXH
      TYPE 528
528   FORMAT('          WHAT IS THE WATER FLOW RATE -SCALE READING-   ',$)
      ACCEPT 111, WTRFLO
      TYPE 529
529   FORMAT('          HOW MANY FUEL CHECKS WERE MADE?  ',$)
      ACCEPT 1041, NCK
1041  FORMAT(I1)
      TYPE 530
530   FORMAT(' ENTER THE FUEL FLOW DATA, MASS IN GRAMS, TIME IN SEC, ',
     1'FOR EACH CHECK (2F10.2)')
      DO 12 I=1, NCK
12    ACCEPT 105, FULFLO(I), T(I)
105   FORMAT(2F10.2)
      TYPE 531
531   FORMAT('          WHAT ARE THE EMISSIONS DATA, HC IN PPM, NO IN ',
     1'PPM, O2, CO2 AND CO IN % (F10.2/) ')
      ACCEPT 111, HC
      ACCEPT 111, NO
      ACCEPT 111, O2
```

```
      ACCEPT 111, CO2
      ACCEPT 111, CO
C
C     THIS EQUATION IS DERIVED FROM THE PAPER "THE METERING OF GASES
C     BY MEANS OF THE ASME SQUARE EDGED ORIFICE WITH FLANGED TAPS." BY
C     LEARY W. A.
C
      W=31.76*DORF**2.0366*((PATM*0.03937-PINOR*0.07369)
     1*((1. + WGR/7000.)/(1. + 1.608*WGR/7000.))*PDEL/
     1(TORIN + 460. ))**0.5
C     THIS CALCULATES THE AIR FLOW IN GRAMS PER SEC
C
      T1=0.
      F =0.
      DO 13 I=1,NCK
      T1 = FULFLO(I)/T(I)
13    F = F + T1
      FM = F/FLOAT(NCK)
C
C     THIS IS THE MEASURED FUEL FLOW RATE
C
      FAR = FM/W
C
C     THIS IS THE MEASURED FUEL AIR RATIO
C
      PHIM = FAR / STOIC
C
C     THIS IS THE MEASURED EQUIVALENCE RATIO
C
      FPERST = FM * 120000.0/(RPM * SPGR )
C
C     THIS IS THE FUEL INJECTED PER STROKE IN MM**3
C
C     CALCULATE THE WATER FLOW RATE USING A LEAST SQUARES
C     FIT FOR THE ROTAMETER CALIBRATION DATA ON 28 JAN 76
```

```
C
      WTRFLO = 0.0479 * WTRFLO - 0.0081
      HREJ = WTRFLO * 60. * (TWOUT-TWIN)
      BMEP = 2.88847 * (PDYB-PDYBZ)
      FMEP = 2.88847 * (PDYFZ-PDYF)
      IMEP = BMEP + FMEP
      BHP  = RPM * (PDYB-PDYBZ)/6000.0
      FHP  = RPM * (PDYFZ-PDYF)/6000.0
      IHP  = BHP + FHP
      MECEFF= BMEP/IMEP
      VOLEFF= W * 3.707 * (TAIRIN + 460.)/(RPM * (PATM * 0.01934
     1-PINL * 0.0361 ))
      SAC =W* 3600./(453.592*IHP)
C
C     ALL EMISSION EQUATIONS ARE BASED ON SAE PAPER 710604
C     BY D. L. STIVENDER   ---- NOTE THAT THE HC ARE MEASURED
C     IN TERMS OF CARBON ATOMS AND THAT AS MEASURED HC IS
C     WET WHILE ALL OTHER QUANITIES ARE MEASURED DRY.
C
      HC = HC/10000.0
      NO = NO/10000.0
      FMWT = 12.01 + 1.008 * HCR
      CH2O = HCR * 0.5 * (CO2 + CO)/(CO/(CO2 * 3.8) + 1.0)
      CH2O = CH2O/100.0
      H2O  = CH2O/(1.0 + CH2O)
      WDR  = 1.0 - H2O
      H2O  = H2O * 100.0
C
      AFR=4.76*(28.96/FMWT)*((CO2+O2+(CO+NO)*0.5)
     1*WDR+0.5*H2O)/(HC+(CO+CO2)*WDR)
      FAREX = 1.0/AFR
C
C     THIS IS THE CALCULATED FUEL AIR RATIO
C
      PHIEX = FAREX/STOIC
```

```
C
C        THIS IS THE CALCULATED EQUIVALENCE RATIO
C
C                CALCULATE THE FUEL CONSUMPTION BASED ON THE AIR FLOW
C        AND THE CALCULATED AFR TO MAKE THE EMISSIONS OUTPUT CONSISTENT.
C

         FM = W * FAREX
         SFC = FM * 3600.0/ IHP
         ISFC = SFC / 453.592
         BSFC = ISFC * IHP / BHP
         ITEFF = 2545.0 / (ISFC * QC )
         DEM = 1./( HC + CO *WDR + CO2*WDR )
         ISCO = (28.01/FMWT) * DEM * WDR * CO * SFC
         ISNO = ( 48.008/FMWT) *DEM *NO * WDR * SFC
         ISHC = ( 83.25/FMWT ) * DEM * (HC/6.) * SFC
C
C        COMMENCE OUTPUT
C
         IX = 13+K*3
         DO 14 I=1,IX
14       TYPE 200
         TYPE 5311, RUN, DA, TE, FU, EL
5311     FORMAT('                        PERFORMANCE SUMMARY FOR THE TCCS ENGINE'/
         1' TEST RUN ',I2,5X,A4,A4,' USING   ',A4,A4,'  FUEL')
         TYPE 532
532      FORMAT('     RPM     INJ START     INJ FINISH     INJ PRESS     ',
         1'NEEDLE LIFT     IGN START     IGN FINISH')
         TYPE 533, RPM, INJS, INJF, INJP, NL, IGNS, IGNF
533      FORMAT('     ',F5.0,7X,I3,12X,I3,11X,I4,12X,F5.3,10X,I3,12X,I3)
         TYPE 534, PHIM, PHIEX
534      FORMAT('            THE MEASURED EQUIVALENCE RATIO= ',F5.3,
         1'          THE CALCULATED EQUIVALENCE RATIO= ',F5.3)
         TYPE 535, IMEP, BMEP, FMEP
535      FORMAT('            IMEP= ',F10.2,3X,'PSI',5X,'BMEP=',F10.2,
```

```
        1 3X,'PSI',5X,'FMEP=',F10.2,3X,'PSI')
        TYPE 536, IHP, BHP, FHP
536     FORMAT('            IHP = ',F10.2,11X,'BHP =',F10.2,11X,'FHP =',
        1 F10.2)
        TYPE 537, MECEFF, ITEFF, VOLEFF
537     FORMAT('    MECH EFF =',F10.3,'  IND THERM EFF =',F10.3,' VOLUME',
        1'TRIC EFF=',F10.3)
        TYPE 538, HREJ, TEXH
538     FORMAT('    HEAT REJECTION TO H2O=',F10.2,' BTU/MIN',5X,'EXH',
        1'AUST TEMP=',F10.1,3X,'DEG F')
        TYPE 539, FPERST
539     FORMAT('                 THE FUEL INJECTED / STROKE =',F10.5,3X,'MM**3' )
        TYPE 540, ISFC, BSFC, SAC
540     FORMAT('            ISFC=',F10.3,5X,'BSFC=',F10.3,5X,
        1'ISAC=',F10.3,5X,'( LBM/HP-HR )')
        TYPE 541, ISCO, ISNO, ISHC
541     FORMAT('            ISCO=',F10.2,5X,'ISNO=',F10.2,5X,
        1'ISHC=',F10.2,5X,'( GR/IHP-HR )')
        TYPE 542
542     FORMAT('                NOX IS IN TERMS OF NO2 AND THE HC IS IN ',
        1'TERMS OF EQUIVALENT HEXANE ')
        DO 15 I=1,13
        TYPE 200
15      CONTINUE
        GO TO 1
99      STOP
        END
```

```
C
C            THIS PROGRAM IS DESIGNED TO COLLECT ON LINE DATA AND TO
C      PERFORM INITIAL DATA PROCESSING INVOLVING STATISTICAL ANALYSIS AND
C      A WORK CALCULATION. THE PROGRAM PROVIDES BOTH PRINT OUT AND DISK
C      STORAGE OPTIONS.
C
C
       DIMENSION IPRES(144), IBUF(288), PSTAT(144,2), DAT(3), TH1(146)
       REAL MEP, HP
C      CNTP IS THE CONTACT PRESSURE THAT IS REQUIRED TO CLOSE THE
C      BALANCE PRESSURE INDICATOR
C      ALL DIMENSIONS FOR THE ENGINE ARE IN CM AND CM**3
       DATA CNTP, PSCALE/ 0.0, 200. /
       DATA BORE, STROKE, CONLEN, VTDC/9.843, 9.843, 16.83, 74.89 /
       DATA PIOVR8,DTR,ATM,CCTIN3/ 0.392699, 0.017453, 14.696, 0.06102 /
C
       VOL(THR) = VTDC + B1*(B3- COS(THR)- SQRT( COS(THR)**2 + B2))
C
       DVDTHR(THR)=B1*CCTIN3*SIN(THR)*(1.+COS(THR)/SQRT(COS(THR)**2+B2))
C
       B1 = PIOVR8 * BORE * STROKE *BORE
       B2 = ( CONLEN *2. / STROKE )**2 - 1.0
       B3 = 1.0 + 2.0 * CONLEN / STROKE
C
       TYPE 802
802    FORMAT('                          !!!WARNING!!!'/
       1'  THE ST1 MUST BE SET TO JUST FIRE BY SLOWLY INCREASING IT FROM',
       1' THE LEFT STOP.'//'  THE REF PULSE IS THE SCOPE TRIGGER',
       1' PULSE SET TO GO MAX AT -185" TDC')
98     TYPE 800
800    FORMAT (//'       WHAT IS THE RUN NUMBER (I2) ?  ',$ )
       ACCEPT 801, IRUN, DAT(3)
801    FORMAT(I2, 10X, A4)
       CALL DATE(DAT)
```

```
      TYPE 804
804   FORMAT(//'        WHAT ANGLE DOES THE BALANCE PRESSURE INDICATOR',
     1' CORRESPOND TO (NEAREST 5 DEGREE) ? (I4)    ', $ )
      ACCEPT 807, IBPI
807   FORMAT(I4)
      TYPE 808
808   FORMAT(//'        WHAT PRESSURE IS THE BALANCE PRESSURE INDICATOR',
     1' SET AT ? (F5.2)     ', $ )
      ACCEPT 809, BPI
809   FORMAT(F5.2)
      BPI = BPI + CNTP
      TYPE 8111
8111  FORMAT(' WHAT IS THE RPM ?    ',$)
      ACCEPT 8112, RPM
8112  FORMAT(F10.3)
500   TYPE 812
812   FORMAT(//'        HOW MANY SAMPLES DO YOU WANT ?  (I3)   ', $ )
      ACCEPT 813, ISAMP
813   FORMAT(I3)
      TYPE 810
810   FORMAT(//' DO YOU WANT TO SEE A FULL CYCLE  ? YES=1 NO=0    ',$)
      ACCEPT 906, LOOK1
      TYPE 8131
8131  FORMAT('                  RELEASE WHEN READY TO RUN',$)
      ACCEPT 8132, NULL
8132  FORMAT(I2)
      TYPE 8133
8133  FORMAT('          ONLINE SAMPLING UNDERWAY DO NOT DISTURB'///)
      ICOUNT = 0
      DO 5 I= 1, 288
           IBUF(I) = 0
5     CONTINUE
      DO 6 I = 1,144
      DO 6 J = 1,2
           PSTAT(I,J) = 0.0
```

```
6       CONTINUE
        LOOK=0
100     DO 1 I=1,288
1       IBUF(I)=0
C
C       JUMP ON BOARD AND COLLECT SAMPLES FOR 2 REVOLUTIONS USING CHANNEL
C       0 AND 10  (OCTAL)
C
        CALL SAMPLE(IBUF,144)
C
C       FIND THE REF PULSE ON CHANNEL 0
C
        IR = 1
        IMAX = IBUF(1)
        DO 2 I=3,287,2
        IF(IBUF(I) .LT. IMAX) GO TO 2
        IMAX = IBUF(I)
        IR = I
2       CONTINUE
C
C       REORDER THE PRESSURE DATA STARTING AT THE REF PULSE
C
        IR = IR +1
        J = 0
        DO 3 I=IR,288,2
        J=J+1
3       IPRES(J) = IBUF(I)
        DO 4 I=2,IR,2
        J=J+1
4       IPRES(J)= IBUF(I)
        ICOUNT =ICOUNT + 1
        IF(ICOUNT .EQ. ISAMP) LOOK=LOOK+LOOK1
C
C       CALIBRATE THE DATA USING BPI, IBPI, PSCALE AND STORE THE ARRAY TO
C       COMPUTE THE FINAL PRESSURE STATISTICS
```

```
C
      IF(LOOK .EQ. 0 ) GO TO 41
      TYPE 701, ICOUNT
701   FORMAT(//'        ICOUNT=   ',I3)
41    CONTINUE
      I = (185 + IBPI ) /5 + 1
      RBPI = (FLOAT( IPRES(I))-2047.)/409.5
      TH=-185.0
      DT= 5.0
      DO 10 I= 2,74
            TH=TH + DT
            K=I-1
            TH1(K)=TH
            PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * PSCALE + BPI
      IF(LOOK .EQ. 0 ) GO TO 42
      TYPE 702, TH, PRESS
702         FORMAT(' THETA= ',F5.0, 5X,'        PRESSURE =   ',F7.3,3X,
     1      'PSI')
42    CONTINUE
            PSTAT(K,2) = PSTAT(K,2) + PRESS
            PSTAT(K,1) = PSTAT(K,1) + PRESS**2
10    CONTINUE
      TH=0.0-TH
      DO 11 I=75,144
      K=I-1
            TH=TH + DT
            TH1(K)=TH
            PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * PSCALE + BPI
            PSTAT(K,2) = PSTAT(K,2) + PRESS
            PSTAT(K,1) = PSTAT(K,1) + PRESS**2
      IF(LOOK .EQ. 0 ) GO TO 43
      TYPE  702, TH, PRESS
43    CONTINUE
11    CONTINUE
      DO 12 I=1,1
```

```
C
        IF(LOOK .EQ. 0 ) GO TO 41
        TYPE 701, ICOUNT
701     FORMAT(//'        ICOUNT=   ',I3)
41      CONTINUE
        I = (185 + IBPI ) /5 + 1
        RBPI = (FLOAT( IPRES(I))-2047.)/409.5
        TH=-185.0
        DT= 5.0
        DO 10 I= 2,74
                TH=TH + DT
                K=I-1
                TH1(K)=TH
                PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * PSCALE + BPI
        IF(LOOK .EQ. 0 ) GO TO 42
        TYPE 702, TH, PRESS
702             FORMAT(' THETA= ',F5.0, 5X,'        PRESSURE =   ',F7.3,3X,
        1       'PSI')
42      CONTINUE
                PSTAT(K,2) = PSTAT(K,2) + PRESS
                PSTAT(K,1) = PSTAT(K,1) + PRESS**2
10      CONTINUE
        TH=0.0-TH
        DO 11 I=75,144
        K=I-1
                TH=TH + DT
                TH1(K)=TH
                PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * PSCALE + BPI
                PSTAT(K,2) = PSTAT(K,2) + PRESS
                PSTAT(K,1) = PSTAT(K,1) + PRESS**2
        IF(LOOK .EQ. 0 ) GO TO 43
        TYPE  702, TH, PRESS
43      CONTINUE
11      CONTINUE
        DO 12 I=1,1
```

```
                 TH=TH +DT
                 PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * PSCALE + BPI
                 K=144
                 TH1(K)=TH
                 PSTAT(K,2) = PSTAT(K,2) + PRESS
                 PSTAT(K,1) = PSTAT(K,1) + PRESS**2
        IF(LOOK .EQ. 0 ) GO TO 44
        TYPE 702, TH, PRESS
44      CONTINUE
12      CONTINUE
        IF ( ICOUNT .EQ. ISAMP ) GO TO 400
C
C       THIS CHECKS TO SEE HOW MANY SAMPLE DATA SETS HAVE BEEN COLLECTED
C       IF NOT MAX COLLECT AGAIN
C
C
        GO TO 100
C
C       PROCESS THE PSTAT ARRAYS TO DETERMINE THE PRESSURE STATISTICS
C
400     SAMP = FLOAT(ISAMP)
        DO 30 I = 1,144
        PSTAT(I,1)=SQRT(ABS(1./(SAMP-1.)*(PSTAT(I,1)-PSTAT(I,2)**2/SAMP)))
                PSTAT(I,2) = PSTAT(I,2)/SAMP
30      CONTINUE
C
C       CALCULATE THE MEAN EFFECTIVE PRESSURE, LIST THE OUTPUT AND PREPARE
C       DATA FILES FOR STORAGE ON THE DISK.
C
C       THE FOLLOWING SECTION CALCULATES THE CYLINDER VOLUME AND THE WORK AT
C       EACH INCREMENT AND PROVIDES FOR PRINT OUT
C
        VDSP = 2. * B1
        TYPE 900
900     FORMAT(//////////'      ON LINE DATA PROGRAM SUMMARY ')
```

```
        TYPE 901, IRUN, DAT(1), DAT(2), DAT(3),RPM
901     FORMAT('          RUN NUMBER ',I2,5X,A4,A4,A4,5X,F7.2,3X,'RPM')
        TYPE 902
902     FORMAT(/'     THETA      VOLUME/VOLUME MAX      MEAN PRESSURE      ',
        1'STAND DEVIATION     LOG(VOL/VOL MAX)      LOG(PRESS ATM)')
C
        DO 40 I = 1,73
                CYVOL = VOL(TH1(I)*DTR)/(VDSF+VTDC)
                CYLN = ALOG10(CYVOL)
                PRLN = ALOG10(PSTAT(I,2)/ATM)
40      TYPE 903, TH1(I), CYVOL, PSTAT(I,2), PSTAT(I,1), CYLN, PRLN
903     FORMAT(6X,F5.0,10X,F7.4,12X,F7.3,13X,F7.3,13X,F8.5,10X,F8.5)
C
        IF( LOOK .EQ. 0 ) GO TO 402
        DO 401 I = 74,144
                CYVOL = VOL(TH1(I)*DTR)/(VDSF+VTDC)
                CYLN = ALOG10(CYVOL)
                PRLN = ALOG10(PSTAT(I,2)/ATM)
401     TYPE 903, TH1(I), CYVOL, PSTAT(I,2), PSTAT(I,1), CYLN, PRLN
402     CONTINUE
        W=0.0
        DO 51 I=1,71,2
        VO1=VOL(TH1(I)*DTR)
        VO2=VOL(TH1(I+2)*DTR)
        F=( VO2-VO1 )* CCTIN3/12.
        F=F * (5.*PSTAT(I,2)+8.*PSTAT(I+1,2)-PSTAT(I+2,2))
51      W=W+F
        WP=0.0
        DO 52 I=73,141,2
        VO1=VOL(TH1(I)*DTR)
        VO2=VOL(TH1(I+2)*DTR)
        F=( VO2-VO1 )* CCTIN3/12.
        F=F * (5.*PSTAT(I,2)+8.*PSTAT(I+1,2)-PSTAT(I+2,2))
52      WP=WP+F
        VO1=VOL(TH1(143)*DTR)
```

```
      VO2=VOL(TH1(1)*DTR)
      F=( VO2-VO1 )* CCTIN3/12.
      F=F * (5.*PSTAT(143,2)+8.*PSTAT(144,2)-PSTAT(1,2))
      WP=WP+F
      PMEP=WP/(VDSP*CCTIN3)
C
      MEP = W/(VDSP*CCTIN3)
      HP  = W*RPM/792000.0
      TYPE 904, MEP, PMEP,  HP
904   FORMAT(/'        THE IMEP = ',F6.2,10X,'THE PMEP = ',F7.2,10X,
     1'THE IHP = ',F6.3///////////)
      ISTR=1
      TYPE 905
905   FORMAT(////'      DO YOU WANT TO STORE THE DATA? 1=YES 0=NO (I1) ',$)
      ACCEPT 906, ISTR
906   FORMAT(I1)
      IF (ISTR .EQ. 0 ) GO TO 97
      TYPE 909
909   FORMAT(/'        ASSIGN A FILE TO THE DATA, IN THE FORM DEV:RUN#.DAT'/)
      CALL ASSIGN(11,'DEV:FILE.EXT',-1)
      DEFINE FILE 11(150,2,U,IT)
C
C     STACK ALL DATA INTO ONE ARRAY FOR STORAGE ON THE  DISK
C
      DO 80 I=1,2
      DO 80 J=1,73
            IX = J + 73*(I-1)
80    WRITE(11'IX) PSTAT(J,I)
      WRITE(11'147) MEP
      WRITE(11'148) HP
      WRITE(11'149) RPM
      WRITE(11'150) PMEP
C
      GO TO 99
97    TYPE 910
```

```
910      FORMAT(/'        DO YOU WANT TO COLLECT MORE DATA? 1=YES 0=NO',$)
         ACCEPT 906, ITALK
         IF (ITALK .EQ. 1 ) GO TO 500
C
99       STOP
         END
```

```
        .TITLE     ONLINE DATA ACQUISITION PROGRAM "SAMPLE"
        .MCALL          .REGDEF
        .REGDEF
        .CSECT  SAMPLE
        LPSADS=170400          ;VECTOR STATUS ADDRESS
        LPSADB=170402          ;VECTOR BUFFER ADDRESS
        TST (R5)+
        MOV (R5)+, R0          ;GET BUFFER POINTER
        MOV @(R5)+, R2         ;GET NUMBER OF POINTS
        CLR @#LPSADS
        CLR @#LPSADB
        MOV #40020, @#LPSADS   ;OPEN CH 0&10 DUAL SAMPLE & HOLD + ST1
1$:     TSTB @#LPSADS          ;WAIT FOR THE FIRST SAMPLE CONVERSION
        BPL 1$
        INC @#LPSADS
        MOV @#LPSADB, (R0)+
2$:     TSTB @#LPSADS          ;WAIT FOR THE SECOND CH CONVERSION
        BPL 2$
        MOV @#LPSADB, (R0)+
        DEC R2                 ;DECREMENT COUNTER
        BGT 1$                 ;GO WAIT FOR ST1 AGAIN
        CLR @#LPSADS
        CLR @#LPSADB
        RTS PC
        .END
```

```
C                ANALIZ
C
C                THIS PROGRAM WILL PREPARE DATA FILES FOR XCLC2
C         USING SUBROUTINE RECALL AND STORE & LIS-183 ENGINE DATA
C
       DIMENSION P(100), TH(100), Z(100), W(100), Q(100), PHITAB(100)    00000050
         DIMENSION P2(100), TH2(100), GAMMA(100), PVG(100)
       LOGICAL TALK                                                      00000060
       INTEGER UNIT                                                      00000070
       COMMON /CHARGE/ PHIAV, DEL, PSI, RESFRK, CHMASS, QLOWER, CFUEL    00000080
       COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,     00000090
      *                RSUBC, RTCAP, RTSML, DSUBC, WO, RPM, TWALL        00000100
       COMMON /VERBOS/ TALK, UNIT                                        00000110
       COMMON /HTDATA/ P1, T1, V1, PM
       COMMON /XPRNTC/PRES, THETA, VBAR, WOVRM, QOVRM, VUAV, VBAV, VB,
      *               EUAV, EBAV, EB, TU, TBAV, TB
C                                                                        00000120
       DATA NREAD, NRITE, NPNCH / 5, 5, 7 /                              00000130
C                                                                        00000140
C                                                                        00000410
C      READ IN PRESSURE DATA, AND SET UP ARRAY OF CRANK ANGLES           00000420
C                                                                        00000430
         CALL RECALL(P2,TH2,RPM)
         TYPE 107
107      FORMAT(////'    WHAT IS THE FUEL H:C RATIO     ',$)
         ACCEPT 901, XCR
         DEL=1./XCR
         TYPE 108
108      FORMAT('    WHAT IS THE LOWER HEATING VALUE FOR THE FUEL     ',$)
         ACCEPT 901, QLOWER
         TYPE 101
101      FORMAT('    WHAT IS THE ISFC     ',$)
         ACCEPT 901, SFC
         TYPE 102
102      FORMAT('    WHAT IS THE ISAC     ',$)
```

```
      TYPE 103
103   FORMAT('   WHAT IS THE MEASURED IHP     ',$)
      ACCEPT 901, XHP
C
C     CALCULATE THE FUEL AND AIR MASS
C
      FMASS =SFC*XHP*453.592/(30.*RPM)
      AMASS = SAC*XHP*453.592/(30.*RPM)
      STOIC=(12.01+1.008*XCR)/((1.+XCR/4.)*137.965)
      PHIAV=(SFC/SAC)/STOIC
C
90    TYPE 104
104   FORMAT('   WHAT IS THE BURNT PRODUCTS EQUIVALENCE RATIO     ',$)
      ACCEPT 901, PHITB
      PSI = 3.764
    CFUEL = 0.00058
C
    BORE  = 9.843
    STROKE= 9.843
    CONLEN= 16.83
    VTDC  = 74.89
    HTDC  = .124
    VCUP  = 62.19
    ACUP  = 72.5
    RSUBC = 2.464
    RTCAP = 1.346
    RTSML = 1.118
    DSUBC = 2.159
C
    TWALL = 400.
C
    TALK  = .TRUE.
    UNIT  = 5
      TYPE 105
105   FORMAT('   WHEN WAS THE START OF INJECTION     ',$)
```

```
      ACCEPT 901,THINJ
      TYPE 1050
1050  FORMAT('    WHEN WAS THE END OF INJECTION    ',$)
      ACCEPT 901, EINJ
      TYPE 106
106   FORMAT('   WHAT DO YOU THINK THE RESIDUAL FRACTION WAS    ',$)
      ACCEPT 901, RESFRK
      QLOWER=QLOWER/1800.
      WO = RPM * 0.37803832
      CHMASS = AMASS+FMASS
      CHMASS = CHMASS/(1.-RESFRK)
C
C     FIND THE START OF INJECTION AND THE NUMBER OF POINTS BEFORE
C     THE EXHAUST VALVE OPENS
C
      DO 10 I=1,73
      IF(TH2(I) .LT. THINJ ) GO TO 10
      K = I
      GO TO 11
10    CONTINUE
11    DO 12 I=K,73
      IF(TH2(I) .LT. 130.) GO TO 12
      KN=I
      GO TO 13
12    CONTINUE
13    I1=0
      DO 14 I=K,KN
      I1=I1+1
      TH(I1) =TH2(I)
      P(I1) = P2(I)
14    CONTINUE
      NPTS = I1
      DO 15 I=1,I1
      IF(TH(I) .LE. EINJ ) GO TO 15
      I3=I
```

```
      GO TO 16
15    CONTINUE
C
C    INITIALIZE ARRAY CONTAINING BURNT PRODUCT PHI'S
C
16    DO 20 I = 1, NPTS
        PHITAB(I) = PHITB
   20 CONTINUE
C
      CALL XCLC2 (P, TH, PHITAB, NPTS, I3, Z, W, Q, GAMMA, PVG  )
901     FORMAT(F15.6)
        TYPE 109
109     FORMAT(///)
        CALL STORE(P,TH,Z,GAMMA,PHITAB,PVG,NPTS)
 1000 CALL EXIT
      END
```

```
C               SUBROUTINE RECALL
C
C               THIS SUBROUTINE WILL RETRIEVE DATA FROM STORAGE FOR FURTHER
C       COMPUTATION AT A LATER DATE
C
C       USAGE
C               CALL RECALL( P, TH, RPM )
C
C       RETURNS
C           P   - AN ARRAY OF PRESSURE VALUES IN ATM
C           TH  - AN ARRAY OF CRANK ANGLE DATA AT WHICH THE PRESSURES OCCUR
C                 (DEG)
C           RPM - THE ACTUAL CALCULATED RPM
        SUBROUTINE RECALL( P, TH, RPM )
        DIMENSION P(75), TH(75), PSTAT(73,2)
        DATA ATM, DELTA / 14.696, 5.0 /
        TH(1) = -180.0
C
C       GENERATE THE THETA ARRAY
C
        DO 1 I=2,73
1               TH(I) = TH(I-1) + DELTA
        TYPE 10
10      FORMAT('        WHAT DATA FILE DO YOU WANT TO USE'/)
        CALL ASSIGN(12,'DEV:FILE.EXT',-1)
        DEFINE FILE 12(150,2,U,IT)
        DO 2 I=1,2
        DO 2 J=1,73
                IX = J + 73 * (I-1)
2       READ(12'IX) PSTAT(J,I)
        READ(12'147)XMEP
        READ(12'148)XHP
        READ(12'149)RPM
        READ(12'150)PMEP
        TYPE 9
```

```
9       FORMAT('   DO YOU WANT TO SEE THE DATA  YES=1 NO=0    ',$)
        ACCEPT 8, MF
8       FORMAT(I1)
        IF(MF .EQ. 0 ) GO TO 16
        TYPE 11
11      FORMAT(//'                              DATA SUMMARY'/
        1'      THETA        PRESSURE        STANDARD DEVIATION')
        TYPE 13, (TH(I), PSTAT(I,2), PSTAT(I,1), I=1,73 )
13      FORMAT(8X,F6.1,7X,F7.2,14X,F7.3)
        TYPE 14, XMEP, PMEP, XHP, RPM
14      FORMAT('        IMEP= ',F10.3,3X,'PMEP= ',F10.3,3X,'HP= ',
        1F10.2,3X,'RPM= ',F7.2)
C
C       CONVERT PRESSURE TO ATM
C
16      DO 15 I=1,73
15      P(I) = PSTAT(I,2)/ATM
        RETURN
        END
```

```
C     PRINT HEADER INFORMATION FOR THIS INVOCATION OF XCLC                      00000120
      SUBROUTINE XPRNT1 (ENOT)                                                  00000040
      COMMON /XPRNTC/ P, TH, VOVRM, WOVRM, QOVRM, VUAV, VBAV, VB,               00000050
     *                EUAV, EBAV, EB, TU, TBAV, TB                              00000060
      COMMON /VERBOS/ TALK,  NRITE                                              00000070
      COMMON /CHARGE/ PHI, DEL, PSI, RESFRN, CHMASS, QLOWER, TREF, CFUEL00000080
C                                                                               00000130
      WRITE (NRITE,100) PHI,CHMASS,ENOT                                         00000140
  100 FORMAT (1H ,'PHI =',F5.2,5X,'CHARGE MASS =',F7.4,                         00000150
     1          ' GRAMS',5X,'INITIAL ENERGY =',F6.1,' CAL/G'//)                 00000160
C                                                                               00000170
C     PRINT OUT TABLE HEADINGS AND FIRST LINE                                   00000180
C                                                                               00000190
      WRITE (NRITE,200)                                                         00000200
  200 FORMAT (1H ,' THETA',4X,'P',6X,'V/M',5X,'W/M',6X,'Q/M',                   00000210
     1          5X,'VU_AV',5X,'VB_AV',3X,'EU_AV',4X,'EB_AV',4X,                 00000220
     2    '       TU',6X,'TB_AV',3X,'GAMMA',3X,'PHIBT',4X,'PV*G',5X,            00000230
     3          'Z',/,1H ,' (DEG)  (ATM)  (CC/G)   (CAL/G)   (CAL/G)',          00000240
     4          '   (CC/G)   (CC/G)  (CAL/G)    (CAL/G) (DEG K)',               00000250
     5          '   (DEG K)   ')                                                00000260
      RETURN                                                                    00000290
      END
C                                                                               00000300
C     PRINT PROPERTIES FOR MIXED CASE                                           00000310
      SUBROUTINE XPRNT2 (X,GAMMA,PHITB,PVG )
      COMMON /XPRNTC/ P, TH, VOVRM, WOVRM, QOVRM, VUAV, VBAV, VB,               00000050
     *                EUAV, EBAV, EB, TU, TBAV, TB                              00000060
      COMMON /VERBOS/ TALK,  NRITE                                              00000070
      COMMON /CHARGE/ PHI, DEL, PSI, RESFRN, CHMASS, QLOWER, TREF, CFUEL00000080
      WRITE (NRITE,500) TH,P,VOVRM,WOVRM,QOVRM,VUAV,VBAV,EUAV,EBAV,             00000340
     1                  TU,TBAV,GAMMA,PHITB,PVG,X                               00000350
  500 FORMAT (1H ,F6.1,F7.2,F8.2,3F9.2,F9.1,F9.2,3F9.1, 4F8.3)                  00000360
      RETURN                                                                    00000354
      END                                                                       00000400
```

```
C*************************************************************************
C
C        SUBROUTINE STORE(P, TH, Z, GAMMA, PHITAB, PVG, NPTS )
C
C
C        THIS ROUTINE WILL ASSIGN A FILE AND STORE THE OUTPUT FROM TEXJOB
C        AND XCLC2
C
C*************************************************************************
         SUBROUTINE STORE(P, TH, Z, GAMMA, PHITAB, PVG, NPTS )
         DIMENSION P(50), TH(50), Z(50), GAMMA(50),PHITAB(50), PVG(50)
C
         TYPE 100
100      FORMAT('     DO YOU WANT TO STORE THE DATA  YES=1     ',$)
         ACCEPT 200, NO
200      FORMAT(I1)
         IF(NO .EQ. 0 ) GO TO 99
         TYPE 101
101      FORMAT('     ASSIGN A FILE TO THE DATA'//)
         CALL ASSIGN(13,'DEV:FILE.EXT',-1)
         DEFINE FILE 13(301,2,U,IT)
         XNPT = FLOAT(NPTS)
         XNPT = XNPT + 0.01
C
C        STACK ALL THE DATA
C
         WRITE(13'1)XNPT
         IX = 1
         DO 10 I=1,NPTS
         IX=I+1
10       WRITE(13'IX) TH(I)
         DO 11 I=1,NPTS
         IX = IX + 1
11       WRITE(13'IX) P(I)
         DO 12 I=1,NPTS
```

```
         IX = IX + 1
12       WRITE(13'IX) Z(I)
         DO 13 I=1,NPTS
         IX = IX + 1
13       WRITE(13'IX) PHITAB(I)
         DO 14 I=1,NPTS
         IX = IX + 1
14       WRITE(13'IX) GAMMA(I)
         DO 15 I=1,NPTS
         IX = IX + 1
15       WRITE(13'IX) PVG(I)
99       RETURN
         END
```

```
C****************** VERSION 2.0 *** 03-24-76 ***************************
C
C     SUBROUTINE XCLC2
C
C     PURPOSE:
C       TO CALCULATE MASS FRACTION OF FUEL BURNED VERSUS CRANK
C       ANGLE FOR A TCCS STRATIFIED CHARGE ENGINE FROM GIVEN
C       PRESSURE-TIME DATA
C
C     USAGE:
C        CALL XCLC2 (P, TH, PHITAB, NPTS, INJ, Z, W, Q, GAMMA, PVG )
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - A VECTOR OF MEASURED COMBUSTION CHAMBER PRESSURES
C                 (ATM ABSOLUTE)
C        TH     - A VECTOR OF CRANK ANGLES (DEGREES ATDC) AT WHICH
C                 THE CORRESPONDING PRESSURE DATA POINTS WERE TAKEN
C        PHITAB- VECTOR OF AVERAGE BURNT PRODUCT EQUIVALENCE RATIOS
C                 CORRESPONDING TO THE ANGLES TH(I) DURING INJECTION
C        NPTS   - NUMBER OF DATA POINTS IN THE VECTORS P, TH, X, W, & Q
C          INJ - THE END OF THE INJECTION PERIOD
C      GIVEN IN COMMON AREA /CHARGE/ :
C        PHIAV - AVERAGE EQUIVALENCE RATIO OF THE CHARGE
C        DEL    - MOLAR C:H RATIO OF THE FUEL
C        PSI    - MOLAR N:O RATIO OF THE CHARGE (APPROX 3.76 FOR AIR)
C        RESFRK- MASS FRACTION OF THE CHARGE THAT IS RESIDUAL
C        CHMASS- TOTAL MASS OF CHARGE (GRAMS)
C        QLOWER- LOWER HEATING VALUE OF THE FUEL (KCAL/G) AT 293 DEG K
C        CFUEL - SPECIFIC HEAT (KCAL/G-DEG K) OF THE LIQUID FUEL
C      GIVEN IN COMMON AREA /ENGINE/ :
C        BORE   - ENGINE BORE (CM)
C        STROKE- ENGINE STROKE (CM)
C        CONLEN- CONNECTING ROD LENGTH (CM) CENTER TO CENTER
C        VTDC   - VOLUME OF THE CHAMBER AT TDC (CM**3)
```

```
C      HTDC   - PISTON CLEARANCE HEIGHT AT TOP DEAD CENTER (CM)
C      VCUP   - CUP VOLUME (CM**3)
C      ACUP   - CUP SURFACE AREA (CM**2)
C      RSUBC  - CUP RADIUS (CM)
C      RTCAP  - RADIUS FROM CUP CENTER TO CENTER OF TORUS CROSS
C               SECTION (CM)
C      RTSML  - RADIUS OF TORUS CROSS SECTION (CM)
C      DSUBC  - CUP DEPTH FROM TOP TO TORUS MIDPLANE (CM)
C      WO     - BDC SWIRL RATE (RAD/SEC)
C      RPM    - ENGINE SPEED (REVOLUTIONS PER MINUTE)
C      TWALL  - CYLINDER WALL TEMPERATURE (DEG K)
C    GIVEN IN COMMON AREA /VERBOS/ :
C      TALK   - A LOGICAL*4 VARIABLE , USED TO SET PRINTOUT MODE
C               IF TRUE, DETAILED LISTINGS OF PROPERTIES OF BURNED AND
C               UNBURNED ELEMENTS WILL BE PRODUCED ON THE FORTRAN FILE
C               WHOSE NUMBER IS GIVEN BY THE VARIABLE 'UNIT'
C               IF FALSE, NO LISTINGS ARE PRODUCED
C      UNIT   - AN INTEGER*4 VARIABLE GIVING THE FORTRAN FILE NUMBER
C               TO WHICH LISTINGS ARE TO BE WRITTEN
C
C   RETURNS:
C      Z      - VECTOR OF CUMULATIVE MASS FRACTION BURNED AT TIME TH(I)
C      W      - VECTOR OF CUMULATIVE WORK DONE AT TIME TH(I)  (CAL)
C      Q      - VECTOR OF CUMULATIVE HEAT LOSS (CAL)
C      PHITAB- VECTOR OF AVERAGE BURNT PRODUCT EQUIVALENCE RATIOS
C               CORRESPONDING TO THE ANGLES TH(I)
C      GAMMA  - VECTOR OF WEIGHTED GAMMA
C       PVG   - VECTOR OF P*VOL**GAMMA
C
C   REMARKS:
C      1) REPORT ANY PROBLEMS TO GORDON MARSH AT 253-3356
C      2) BURNT ZONE ASSUMED UNIFORM (FULLY MIXED)
C      3) ANY EGR ASSUMED TO BE AT AVERAGE EQUIVALENCE RATIO OF CHARGE
C
C   SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
```

```
C         HPROD, AFTEMP, UPROP2, ADCOMP, TSUBU2, HEAT2, XPRINT2, GASVEL
C
C     METHOD:
C         SIMPLE THERMODYNAMIC MODEL USING MASS AND ENERGY CONSERVATION
C         WITH AN APPROXIMATE FORMULA FOR HEAT TRANSFER (WOSCHNI'S
C         CORRELATION)
C
C***********************************************************************
      SUBROUTINE XCLC2 (P, TH, PHITAB, NPTS, INJ, Z, W, Q, GAMMA, PVG )
C
      DIMENSION P(NPTS), TH(NPTS), Z(NPTS), W(NPTS), Q(NPTS),
     *          PHITAB(NPTS), GAMMA(NPTS), PVG(NPTS)
      COMMON /CHARGE/ PHIAV, DEL, PSI, RESFRK, CHMASS, QLOWER, CFUEL
      COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,
     *                RSUBC, RTCAP, RTSML, DSUBC, WO, RPM, TWALL
      COMMON /VERBOS/ TALK, UNIT
      COMMON /HTDATA/ P1, T1, V1, PM
      COMMON /XPRNTC/ PRES, THETA, VBAR, WOVRM, QOVRM, VUAV, VBAV, VB,
     *                EUAV, EBAV, EB, TU, TBAV, TB
C
      LOGICAL FIRST, TALK
      REAL K1, K2, K3
      INTEGER UNIT
C
      DATA ERLIM /.001/, MAXITS /20/, MAXHTR /3/
      DATA PIOVR8 /.39269908/, DTR /.01745329/
      DATA R /1.9869/, PSCALE /2.42173E-2/
      DATA TBMIN, TBMAX /400., 4000./
C
C     SET UP STATEMENT FUNCTIONS FOR COMBUSTION CHAMBER VOLUME, THE
C     DERIVATIVE OF VOLUME WITH RESPECT TO CRANK ANGLE, AND PISTON
C     CLEARANCE HEIGHT.  ALSO ONE TO LIMIT 0 <= X <= 1
C
      VOL(THR) = VTDC + B1*(B3 - COS(THR) - SQRT(COS(THR)**2 + B2))
      DVDTHR(THR) = B1*SIN(THR)*(1. + COS(THR)/SQRT(COS(THR)**2 + B2))
```

```
      HT(THR)   = HTDC + S1*(B3 - COS(THR) - SQRT(COS(THR)**2 + B2))
      CLIF(XX) = AMAX1(0.0 , AMIN1(1.0,XX))
C
C     SET UP PARAMETERS FOR THE STATEMENT FUNCTIONS AND COMPUTE WORK
C     DONE
C
      B1     = PIOVR8*BORE*BORE*STROKE
      B2     = (CONLEN*2./STROKE)**2 - 1.0
      B3     = 1.0 + 2.*CONLEN/STROKE
      S1     = STROKE/2.0
      GAMMAB = 0.
C
      W(1)   = 0.
      FLAST = P(1)*PSCALE*DVDTHR(DTR*TH(1))
      DO 10 I = 2, NPTS
         F      = P(I)*PSCALE*DVDTHR(DTR*TH(I))
         W(I)   = W(I - 1) + .5*(FLAST + F)*(TH(I) - TH(I-1))*DTR
         FLAST = F
   10 CONTINUE
C
C        COMPUTE AMASS, FMASS, AND RMASS
C
      EPS    = (4.0*DEL)/(1.0 + 4.0*DEL)
      F      = (8.*EPS + 4.)/(28.*PSI + 32.)
        AMASS = (1.-RESFRK)*CHMASS/( 1.+PHIAV*F)
        FMAST = AMASS * F * PHIAV
        RMASS = CHMASS - AMASS - FMAST
        DMASS = FMAST / FLOAT(INJ)
        RESID = RESFRK
C
C        SET FMASS = THE FIRST INJCETION INCREMENT
C
        FMASS = DMASS
        CHMASS = AMASS + RMASS + FMASS
        RESFRK = RMASS/CHMASS
```

```
      PHIAT = PHIAV
C
C     SET UP INITIAL VALUES BEFORE LOOPING THROUGH TIME
C
      Z(1)  = 0.
      Q(1)  = 0.
      THETA = TH(1)
      PHIB  = PHITAB(1)
      PRES  = P(1)
      CVOL  = VOL(DTR*THETA)
      VBAR  = CVOL/CHMASS
C
C     INITIALIZE CONSTANTS RELATING X, Y, AND Z
C
C     CALCULATE INITIAL TEMPERATURE OF UNBURNED CHARGE
C
      RHO   = ( AMASS + RMASS )/CVOL
      TMOL  = PSI + (1.0 - RESFRK)
      IF (PHIAV .LE. 1.0) TMOL = TMOL + (1.0 + PHIAV*(1.-EPS))*RESFRK
      IF (PHIAV .GT. 1.0) TMOL = TMOL + (2.0 - EPS)*PHIAV*RESFRK
      XMAV  = (32. + 28.*PSI + (8.*EPS + 4.)*PHIAV*RESFRK)/TMOL
      TU    = PRES*PSCALE*XMAV/(RHO*R)
C
C     GET INITIAL PROPERTIES OF THE FUEL
C
      VUFAV = TU*82.057*DEL/(96.08*DEL + 8.06)/PRES
      EUFAV = (ABS(QLOWER) - (115.596-21.542*EPS)/(8.*EPS + 4.))*1000.
C
C     GET INITIAL PROPERTIES OF UNBURNED CHARGE
C
      CALL UPROP2 (PRES, TU, PHIAV, DEL, PSI, RESID , ENTHLP, CSUBP,
     *              CSUBT, RHO, DRHODT, DRHODP)
      EO    = ENTHLP*1000. - PRES*PSCALE/RHO
      VUAV = 1.0/RHO
      EUAV = EO
```

```
      GAMMAU = (TU*DRHODT*DRHODT*PSCALE)/(RHO*RHO*DRHODP*CSUBP)          00001660
      GAMMAU = 1.0 / (1.0 - GAMMAU)                                       00001670
        GAMMA(1) = GAMMAU
        PNOT = PRES
        VNOT = CVOL
        PVG(1) = 1.0
      IF (TALK)  CALL XPRNT1 (E0)                                         00001860
C
C       GET THE ACTUAL PHIAV AT CURRENT THETA
C
        PHIAV = FMASS / ( AMASS * F )
        C1 = (1.0 + PHIAV*F)/((AMASS+FMASS)/CHMASS)
      C2SAVE= (1.0 + F*PHIAV*RESFRK)/(1.0 - RESFRK)                       00001380
        C2 = C2SAVE + F*PHIB
        K1 = F*PHIAV/C1
        K2 = F*PHIB/C2
        K3 = K2/K1
C                                                                         00001680
C     GET INITIAL HEAT TRANSFER RATE                                      00001690
C                                                                         00001700
      P1 = PRES                                                           00001710
      V1 = CVOL                                                           00001720
      T1 = TU                                                             00001730
      PM = PRES                                                           00001740
      CALL AFTEMP (PRES, TU, TU, TU, 298., CFUEL, QLOWER, PHIB, DEL,      00001750
     *             PSI, RESFRK, TBAV)                                     00001760
      CALL HEAT2 (PRES, THETA, TU, TBAV, 0.0, DQBDTL, DQUDTL)             00001770
      CALL HPROD (PRES, TBAV, PHIB, DEL, PSI, ENTHLP, CSUBP, CSUBT, RHO,00001780
     *            DRHODT, DRHODP)                                         00001790
      VBAV  = 1.0/RHO                                                     00001800
      EBAV  = ENTHLP*1000. - PRES*PSCALE/RHO                              00001810
      QOVRM = 0.                                                          00001820
      WOVRM = 0.                                                          00001830
C                                                                         00001850
        IF (TALK)  CALL XPRNT2 (Z(1),GAMMA(1),PHITAB(1),PVG(1))
```

```
C
C-----------------------------------------------------------------------
C
C     START LOOP THROUGH TIME; INITIALIZE PROPERTIES CONSTANT FOR
C     GIVEN TIME
C
C-----------------------------------------------------------------------
      DO 200 I = 2, NPTS
C
C
C       CORRECT THE CHARGE MASS DURING INJECTION
C
        IF(I .GT. INJ) GO TO 88
        FMASS = FMASS + DMASS
        CHMASS = FMASS + AMASS + RMASS
        PHIAV = FMASS/(AMASS*F)
        RESFRK = RMASS/CHMASS
        PHITAB(I) = PHITAB(I-1)
        MAE = FMASS / (PHITAB(I)*F)
88      IF(I .LT. (INJ+3) ) GO TO 87
89      CHT = HT(DTR*TH(I-1))
        CX = CLIP(X)
        CALL PLUME( CHT, DELT, VBAV, VUAV, CX, AENT )
        MAE = MAE + AENT
        PHITAB(I) = FMASS / (MAE*F)
        IF (PHITAB(I) .LT. PHIAT ) PHITAB(I) = PHIAT
87      CONTINUE
         TBLAST = TBAV
         QLAST  = Q(I - 1)
         PLAST  = PRES
         TULAST = TU
C
         THETA = TH(I)
         PRES  = P(I)
         DELT  = (THETA - TH(I-1))/(6.0*RPM)
```

```
      CVOL   = VOL(DTR*THETA)                                        00002040
      PM     = P1*(V1/CVOL)**GAMMAU                                  00002050
      VBAR   = CVOL/CHMASS                                           00002060
      WOVRM  = W(I)/CHMASS                                           00002070
      QOVRM  = (QLAST + DQBDTL*DELT)/CHMASS                          00002080
      TU     = TSUBU2 (PRES, PLAST, TULAST, ERLIM)                   00002090
     VUFAV = TU * 82.057 * DEL/(96.08*DEL+8.06)/PRES
99      PHIB   = PHITAB(I)                                           00002100
     C1      = (1. + PHIAV*F)/((AMASS+FMASS)/CHMASS)
    C2SAVE= (1.0 + F*PHIAV*RESFRK)/(1.0 - RESFRK)                    00001380
      C2     = C2SAVE + F*PHIB                                       00002110
      K2     = F*PHIB/C2                                             00002120
      K3     = (PHIB*C1)/(PHIAV*C2)                                  00002121
C                                                                    00002150
C     CALCULATE AVERAGE PROPERTIES OF UNBURNED CHARGE                00002160
C                                                                    00002170
      CALL UPROP2 (PRES, TU, PHIAT, DEL, PSI, RESID , ENTHLP, CSUBP, 00002180
     *             CSUBT, RHO, DRHODT, DRHODP)                       00002190
      VUAV = 1.0/RHO                                                 00002200
      EUAV = ENTHLP*1000. - PRES*PSCALE/RHO                          00002210
      VU1TL= K1*VUFAV + (1.0 - K1)*VUAV                              00002211
      VU2TL= K2*VUFAV + (1.0 - K2)*VUAV                              00002212
      EU1TL= K1*EUFAV + (1.0 - K1)*EUAV                              00002213
      EU2TL= K2*EUFAV + (1.0 - K2)*EUAV                              00002214
      EBAR = E0 - WOVRM - QOVRM                                      00002230
C                                                                    00002240
C     SOLVE CONSERVATION EQUATIONS.                                  00002250
C     FIRST ITERATE TO GET AVERAGE BURNED GAS TEMPERATURE            00002260
C                                                                    00002270
 100  DO 130 IHEAT = 1, MAXHTR                                       00002280
         DO 110 NCOUNT = 1, MAXITS                                   00002290
            CALL HPROD (PRES, TBLAST, PHIB, DEL, PSI, ENTHLP, CSUBP, 00002300
     *                  CSUBT, RHO, DRHODT, DRHODP)                  00002310
            DVBDTB = -DRHODT/(RHO*RHO)                               00002321
            DEBDTB = CSUBP - PRES*PSCALE*DVBDTB                      00002322
```

```
            VBAV    = 1./RHO                                          00002330
            EBAV    = ENTHLP*1000. - PRES*PSCALE/RHO                  00002340
            DGDTB   = (VBAR - VU1TL)/((EBAR - EU1TL)*(VBAV-VU2TL)**2) 00002370
     *                 *((VBAV - VU2TL)*DEBDTB - (EBAV - EU2TL)*DVBDTB) 00002380
            G       = (VBAR - VU1TL)*(EBAV - EU2TL)/                  00002390
     *                  ((EBAR - EU1TL)*(VBAV - VU2TL))  -  1.0       00002391
            TBAV    = TBLAST - G/DGDTB                                00002400
            IF ( ABS(1. - TBAV/TBLAST) .LT. ERLIM)  GO TO 120          00002410
            TBAV    = AMAX1 (TU , AMIN1 (TBMAX,TBAV))                 00002401
            TBLAST = TBAV                                             00002420
  110     CONTINUE                                                    00002430
C                                                                     00002440
C         THEN CALCULATE X DIRECTLY, AND UPDATE HEAT TRANSFER         00002450
C         ESTIMATE                                                    00002460
C                                                                     00002470
  120     X = (VBAR - VU1TL)/(VBAV - VU2TL)                           00002480
          CALL HEAT2 (PRES, THETA, TU, TBAV, VBAV*CHMASS*CLIP(X),     00002490
     *                DQBDT, DQUDT)                                   00002500
          Q(I)   = QLAST + .5*(DQBDT + DQBDTL)*DELT                   00002510
          QOVRM = Q(I)/CHMASS                                         00002520
          EBAR   = EO - WOVRM - QOVRM                                 00002530
          TBLAST = TBAV                                               00002540
  130   CONTINUE                                                      00002560
      GAMMAB=TBLAST*DRHODT*DRHODT*PSCALE/(RHO*RHO*DRHODP*CSUBP)       00002562
      GAMMAB = 1.  /(1.- GAMMAB)                                      00002564
        DQBDTL = DQBDT                                                00002570
        Z(I)    = K3*X*FMASS/FMAST                                    00002581
       XF=CLIP(Z(I))
      GAMMA(I) = ((1.-XF)*GAMMAU+XF*GAMMAB)
 150   PVG(I) = (P(I)*CVOL**GAMMA(I))/(PNOT*VNOT**GAMMA(I))
        IF (TALK) CALL XPRNT2(Z(I),GAMMA(I),PHITAD(I),PVG(I))         00002590
  200 CONTINUE                                                        00002600
C                                                                     00002610
      RETURN                                                          00002620
      END                                                             00002630
```

```
C******************* VERSION 1.0 *** 11-03-74 ***************************
C
C     SUBROUTINE GASVEL
C
C     PURPOSE:
C        TO CALCULATE LOCAL MEAN GAS VELOCITIES IN THE TCCS ENGINE
C
C     USAGE
C        CALL GASVEL (THETA, VOLB, VR3, VT3, VZ3)
C
C     DESCRIPTION OF PARAMETERS:
C       GIVEN:
C        THETA - CRANK ANGLE (DEG ATDC)
C        VOLB  - TOTAL VOLUME OF BURNED GAS IN CYLINDER (CM**3)
C      GIVEN IN COMMON AREA /ENGINE/ :
C        BORE  - ENGINE BORE (CM)
C        STROKE- ENGINE STROKE (CM)
C        CONLEN- CONNECTING ROD LENGTH (CM) CENTER TO CENTER
C        VTDC  - VOLUME OF THE CHAMBER AT TDC (CM**3)
C        HTDC  - PISTON CLEARANCE HEIGHT AT TOP DEAD CENTER (CM)
C        VCUP  - CUP VOLUME (CM**3)
C        ACUP  - CUP SURFACE AREA (CM**2)       (NOT USED)
C        RSUBC - CUP RADIUS (CM)
C        RTCAP - RADIUS FROM CUP CENTER TO CENTER OF TORUS CROSS
C                SECTION (CM)
C        RTSML - RADIUS OF TORUS CROSS SECTION (CM)
C        DSUBC - CUP DEPTH FROM TOP TO TORUS MIDPLANE (CM)
C        WO    - BDC SWIRL RATE (RAD/SEC)
C        RPM   - ENGINE SPEED (REVOLUTIONS PER MINUTE)   (NOT USED)
C        TWALL - CYLINDER WALL TEMPERATURE (DEG K)       (NOT USED)
C       RETURNS:
C        VR3   - AVERAGE RADIAL VELOCITY AT CUP EDGE (CM/SEC)
C        VT3   - AVERAGE AZIMITHAL (SWIRL) VELOCITY INSIDE
C                THE CUP (CM/SEC)
C        VZ3   - AVERAGE AXIAL VELOCITY AT CUP MOUTH (CM/SEC)
```

```
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS USED:  NONE
C
C     REMARKS:
C        1) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
C        2) NOT CORRECTED FOR CONDITIONS ARISING FROM COMBUSTION
C
C     METHOD:
C        SIMPLE CONTROL VOLUME ANALYSIS USING CONTINUITY EQUATION
C
C***********************************************************************
C
      SUBROUTINE GASVEL (THETA, VOLB, VR3, VT3, VZ3)
      COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,
     *                RSUBC, RTCAP, RTSML, DSUBC, WO, RPM, TWALL
      REAL K, L, M, LOVAP1, INTGRL
      DATA PI /3.1415926535/, DTR /.01745329/
C
C     INITIALIZE CONSTANTS OF THE GEOMETRY
C
      R      = BORE/2.0
      M      = 4.0*CONLEN*CONLEN/(STROKE*STROKE) - 1.0
      LOVAP1 = 2.0*CONLEN/STROKE + 1.0
      B      = RSUBC/R
      VSCALE = SQRT(1.0 - .25/M) * (1.0 + 1.0/SQRT(M*M + 4.*M + 1.0))
      RRAT   = RTCAP/RTSML
C
      K      = VCUP/(PI*R*R)
      XO     = (HTDC + STROKE)/K
      INTGRL = PI*RRAT*(RTSML**5)*(.375 + .5*RRAT*RRAT)
      G      = DSUBC*(B**4)/K + 4.0*INTGRL/(K*R**4)
C
C     CALCULATE QUANTITIES DEPENDENT UPON THETA
C
      COSTH  = COS (DTR*THETA)
```

```
      SINTH  = SIN (DTR*THETA)
      S      = SQRT (COSTH*COSTH + M)
      TEMP   = LOVAP1 - COSTH - S
C
      HT     = HTDC + .5*STROKE*TEMP
      CVOL   = VTDC + .5*STROKE*PI*R*R*TEMP
      VPRAT  = - SINTH*(1.0 + COSTH/S)/VSCALE
C
      X      = HT/K
      BTOM2  = 1.0/(B*B)
C
C     CALCULATE DIMENSIONLESS VELOCITY RATIOS AS IN NOTES
C
      VRRAT  = (BTOM2 - 1.0)*VPRAT*RSUBC/(2.0*K*X*(1.0 + X))
      VZRAT  = (BTOM2 - 1.0)*VPRAT/((1.0 + X)*(1.0+ B*B*X))
      VTRAT  = BTOM2 - (BTOM2 - 1.0)*(X*(1.0+XO))/(XO*(1.0+X))
C
C     GET APPROPRIATE MAXIMUM PISTON SPEED AND CALCULATE VELOCITIES
C
      VPMAX  = PI*RPM*STROKE*VSCALE/30.
      VR3    = VRRAT*VPMAX
      VT3    = VTRAT*WO*RSUBC
      VZ3    = VZRAT*VPMAX
C
      RETURN
        END
```

```
C******************** VERSION 1.0 *** 11-03-74 ***************************
C
C     SUBROUTINE HEAT2
C
C     PURPOSE:
C        TO CALCULATE HEAT TRANSFER IN A TCCS STRATIFIED CHARGE ENGINE
C
C     USAGE:
C        CALL HEAT2 (P, THETA, TU, TB, VOLB, DQBDT, DQUDT)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE CYLINDER PRESSURE (ATM)
C        THETA  - CORRESPONDING CRANK ANGLE (DEG ATDC)
C        TU     - AVERAGE UNBURNED GAS TEMPERATURE (DEG K)
C        TB     - AVERAGE BURNED GAS TEMPERATURE (DEG K)
C        VOLB   - VOLUME OF THE BURNED GAS (CM**3)
C      GIVEN IN COMMON AREA /ENGINE/ :
C        BORE   - ENGINE BORE (CM)
C        STROKE- ENGINE STROKE (CM)
C        CONLEN- CONNECTING ROD LENGTH (CM) CENTER TO CENTER
C        VTDC   - VOLUME OF THE CHAMBER AT TDC (CM**3)
C        HTDC   - CLEARANCE HEIGHT AT TDC (CM)
C        VCUP   - CUP VOLUME (CM**3)
C        ACUP   - CUP SURFACE AREA (CM**2)
C        RSUBC - CUP RADIUS (CM)
C        RTCAP - RADIUS FROM CUP CENTER TO CENTER OF TORUS CROSS
C                SECTION (CM)
C        RTSML - RADIUS OF TORUS CROSS SECTION (CM)
C        DSUBC - CUP DEPTH FROM TOP TO TORUS MIDPLANE (CM)
C        WO     - BDC SWIRL RATE (RAD/SEC)
C        RPM    - ENGINE SPEED (REVOLUTIONS PER MINUTE)  (NOT USED)
C        TWALL - CYLINDER WALL TEMPERATURE (DEG K)
C      GIVEN IN COMMON AREA /HTDATA/ :
C        P1     - PRESSURE AT REFERENCE TIME (ATM)
```

```
C        T1     - TEMPERATURE AT REFERENCE TIME (DEG K)
C        V1     - VOLUME AT REFERENCE TIME (CM**3)
C        PM     - EQUIVALENT PRESSURE IN THE MOTORING ENGINE (ATM)
C      RETURNS:
C        DQBDT - HEAT TRANSFER RATE FROM BURNED GAS TO THE WALL
C                (CAL/SEC)
C        DQUDT - HEAT TRANSFER RATE FROM UNBURNED GAS TO THE WALL
C                (CAL/SEC)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C        GASVEL
C
C     REMARKS:
C        1) ASSUMED TOROIDAL FLAME FRONT
C        2) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
C
C     METHOD:
C        WOSCHNI'S CORRELATION (SEE SAE PAPER NUMBER 670931)
C
C*************************************************************************
C
      SUBROUTINE HEAT2 (P, THETA, TU, TB, VOLB, DQBDT, DQUDT)
      COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,
     *                RSUBC, RTCAP, RTSML, DSUBC, WO, RPM, TWALL
      COMMON /HTDATA/ P1, T1, V1, PM
C
      DATA PI /3.14159265/, DTR /.01745329/
      DATA PSCL /.967836/
      DATA ERLIM /.005/, MAXITS /50/
C
      VOL(THR) = VTDC + VDSP*(H1 - COS(THR) - SQRT(COS(THR)**2 + H2))
      HT(THR)  = HTDC + HDSP*(H1 - COS(THR) - SQRT(COS(THR)**2 + H2))
C
      H1   = 1.0 + 2.0*CONLEN/STROKE
      H2   = (2.0*CONLEN/STROKE)**2 - 1.0
```

```
      VDSP = STROKE*PI*BORE*BORE/8.0
      HDSP = STROKE/2.0
C
C     CALCULATE HEAT TRANSFER AREAS.  FOR NOW, USE SIMPLE APPORTIONMENT
C
      RAD  = BORE/2.0
      CHT  = HT(DTR*THETA)
      CVOL = VOL(DTR*THETA)
      VB   = AMIN1 ( CVOL, AMAX1(0.,VOLB))
      AREA = ACUP + PI*RAD*(RAD + 2.0*CHT)
      AB   = ACUP
      IF (VB .LE. VCUP)  AB = ACUP*(VB/VCUP)**.666666666
      AU   = AREA - AB
C
C
C     GET GAS VELOCITIES INSIDE THE CUP
C
      CALL GASVEL (THETA, VOLB, VR3, VT3, VZ3)
C
C     CALCULATE THE HEAT TRANSFER COEFFICIENT USING WOSCHNI'S EQUATION
C     (CONVERT TO CAL/CM**2 SEC DEG_K)
C
      C1 = 2.28
      C2 = 3.24E-3
      CM = .01*SQRT(VT3*VT3 + VR3*VR3 + VZ3*VZ3)
C
      DELP  = AMAX1(P - PM , 0.)
      FACTR = 110.*(BORE/100.)**(-.2)*(P*PSCL)**(.8)
      FACTR = FACTR*((C1*CM + C2*T1*(CVOL/V1)*(DELP/P1)))**(.8)
C
      HB = FACTR*(TB**(-.53))/36000.
      HU = FACTR*(TU**(-.53))/36000.
C
C     THEN CALCULATE HEAT TRANSFER RATES AND RETURN
C
```

```
      DQBDT = AB*HB*(TB - TWALL)
      DQUDT = AU*HU*(TU - TWALL)
C
      RETURN
        END
```

```
C*****************************************************************
C
C               SUBROUTINE PLUME
C
C       THIS ROUTINE WILL CALCULATE THE AMOUNT OF AIR ENTRAINED
C       IN THE BURNING PLUME OF COMBUSTION PRODUCTS IN A TCCS ENGINE
C       USING THE MIXING MODEL PROPOSED BY JAIN.
C
C       USAGE:
C               CALL PLUME(CHT, DELT, VBAV, VUAV, CX, AENT )
C
C       DESCRIPTION OF PARAMETERS:
C         GIVEN:
C               CHT   -COMBUSTION CHAMBER HEIGHT
C               DELT  -TIME INTERVAL FOR ENTRAINMENT
C               VBAV  -SPECIFIC VOLUME OF THE BURNT GAS
C               VUAV  -SPECIFIC VOLUME OF THE AIR AND RESIDUAL
C               CX    -A CLIPPED FRACTION OF CHARGE MASS BURNT
C
C         RETURNS:
C               AENT  -THE MASS OF AIR ENTRAINED IN THAT TIME STEP
C
C         INTERNALLY DEFINED VALUES:
C               RSP   -THE SPARK PLUG RADIUS
C               DVAL  -THE INTAKE VALVE DIAMETER
C               LVAL  -THE INTAKE VALVE LIFT
C               EFFV  -THE AVERAGE VOLUMETRIC EFFICIENCY
C               ALPHA -AN ADJUSTABLE ENTRAINMENT COEFFICIENT
C
C*******************************************************************
C
        SUBROUTINE PLUME(CHT, DELT, VBAV, VUAV, CX, AENT )
        COMMON/CHARGE/PHIAV,DEL,PSI,RESFRK,CHMASS,QLOWER,CFUEL
        COMMON/ENGINE/BORE,STROKE,CONLEN,VTDC,HTDC,VCUP,ACUP,
        *                RSUBC,RTCAP,RTSML,DSUBC,WO,RPM,TWALL
```

```
      REAL LVAL
      RSP = 1.9
      DVAL = 4.0
      LVAL = 1.558
      EFFV = 0.87
      ALPHA = 0.05
      PL = RSUBC - RSP
      DCP = 2.* RSUBC
      RPL1 = PL
      RPL2 = RSP
      RPL3 = BORE/2. - RSP
      VB1 = 19.75 * RSP * PL**2
      VB2 = 12.57 * CHT * RSP**2 + 0.7854 *(RSUBC - CHT)*DCP**2
      VB3 = 0.785 * CHT * BORE**2 + 0.7854*(BORE/2.-RSP+PL-CHT)
     1*DCP**2
      VBA = VBAV * CHMASS * CX
      IF ( VBA .LE. VB1) GO TO 120
      IF ( VBA .LE. VB2) GO TO 110
      IF ( VBA .LE. VB3) GO TO 100
      SE3 = 0.7854 * DCP**2
      SE = SE3
      GO TO 900
100   RPL = RPL2+(RPL3-RPL2)*((VBA-VB2)/(VB3-VB2))**0.333
      SE = 6.28 * (RSP + RPL ) * CHT +0.7854 * DCP**2
      GO TO 900
110   RPL = RPL1 + (RPL2-RPL1)*((VBA-VB1)/(VB2-VB1))**0.333
      SE=6.28*(RSP+RPL)*CHT + 3.14 * (3.*(RSP-RPL)+RSUBC)*(RPL+PL)
      GO TO 900
120   RPL = SQRT(VBA/19.75*RSP)
      SE = 39.4 * RSP* RPL
900   UE = 0.23*EFFV*STROKE*RPM*BORE**2/(DVAL*LVAL)*0.5
      AENT = ALPHA * SQRT(1./(VBAV*VUAV))*SE*UE*DELT
      RETURN
      END
```

```
C*********************************************************************
C
C     SUBROUTINE AFTEMP
C
C     PURPOSE:
C        TO CALCULATE ADIABATIC FLAME TEMPERATURES FOR HC-AIR
C        COMBUSTION
C
C     USAGE:
C        CALL AFTEMP (P,TA,TR,TF,TREF,CFUEL,QLOWER,PHI,DEL,PSI,
C                     RESFRK,TPROD)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE PRESSURE (ATM)
C        TA     - INDUCTED AIR TEMPERATURE (DEG K)
C        TR     - TEMPERATURE OF THE RESIDUAL FRACTION (IN DEG K)
C        TF     - FUEL TEMPERATURE (DEG K)
C        TREF   - TEMPERATURE AT WHICH HEATING VALUE WAS MEASURED
C                 (DEG K)
C        CFUEL  - SPECIFIC HEAT OF THE FUEL (KCAL/G -DEG K)
C        QLOWER- LOWER HEATING VALUE OF THE FUEL (KCAL/G)
C        PHI    - EQUIVALENCE RATIO OF THE MIXTURE
C        DEL    - MOLAR C:H RATIO
C        PSI    - MOLAR N:O RATIO
C        RESFRK- RESIDUAL FRACTION AS A MASS FRACTION OF TOTAL CHARGE
C      RETURNS:
C        TPROD  - TEMPERATURE OF THE RESULTANT COMBUSTION PRODUCTS
C                 (DEG K)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C        HPROD,TEMP
C
C     REMARKS:
C        1) TREF MUST BE < 600 DEG K FOR REASONABLE ACCURACY, SINCE
```

```
C          IN THE PRESENT IMPLEMENTATION THE ENTHALPIES OF FORMATION    AFTP 360
C          OF CO2 AND H2O ARE ASSUMED TO BE TEMPERATURE INDEPENDENT     AFTP 370
C                                                                       AFTP 390
C     METHOD:                                                           AFTP 400
C        SEE MATHEMATICAL NOTES                                         AFTP 410
C                                                                       AFTP 420
C***********************************************************************AFTP 430
      SUBROUTINE AFTEMP (P,TA,TR,TF,TREF,CFUEL,QLOWER,PHI,DEL,PSI,      AFTP 440
     1                   RESFRK,TPROD)                                  AFTP 450
C                                                                       AFTP 460
      DATA ROVR2/.99345E-3/,CPGUES/.30E-3/                              AFTP 470
      DATA DHCO2,DHH2O/-94.054,-57.798/                                 AFTP 480
C                                                                       AFTP 490
C     STATEMENT FUNCTION FOR ENTHALPY OF AIR                            AFTP 500
      HSUBA(T) = (7.*(1. + PSI)*T + 4460./(EXP(2230./T) - 1.)           AFTP 510
     1      + PSI*6680./(EXP(3340./T)- 1.)) * ROVR2/AIRWT               AFTP 520
C                                                                       AFTP 530
      EPS = (4.*DEL)/(1. + 4.*DEL)                                      AFTP 540
      AIRWT = 32. + 28.*PSI                                             AFTP 550
      FUELWT = (8.*EPS + 4.)*PHI                                        AFTP 560
      TOTWT = AIRWT + FUELWT                                            AFTP 570
C                                                                       AFTP 580
C     GET ENTHALPY OF THE RESIDUAL                                      AFTP 590
C                                                                       AFTP 600
      CALL HPROD(P,TR,PHI,DEL,PSI,HSUBP,DUMY,DUMY,DUMY,DUMY,DUMY)       AFTP 610
      HSUBP = RESFRK*HSUBP                                              AFTP 620
C                                                                       AFTP 630
C     ADD THE ENTHALPY OF THE AIR                                       AFTP 640
C                                                                       AFTP 650
      HSUBP = HSUBP + HSUBA(TA)*(1.0 - RESFRK)*AIRWT/TOTWT              AFTP 660
C                                                                       AFTP 670
C     GET HEAT OF FORMATION OF THE FUEL AND ADD TOTAL FUEL ENTHALPY     AFTP 680
C                                                                       AFTP 690
      DHFUEL = ABS(QLOWER) + (EPS*DHCO2 + 2.*(1.-EPS)*DHH2O)/FUELWT*PHI AFTP 700
      HSUBP = HSUBP + (1.- RESFRK)*(DHFUEL + CFUEL*TF)*FUELWT/TOTWT     AFTP 710
```

```
C                                                                       AFTP 720
C     SET PARAMETERS FOR TEMP                                           AFTP 730
C                                                                       AFTP 740
      TGUESS = TA + ABS(QLOWER)/CPGUES*FUELWT/TOTWT                     AFTP 750
      ERMAX = .001                                                      AFTP 760
      MAXITS = 50                                                       AFTP 770
C                                                                       AFTP 780
      CALL TEMP(P,TGUESS,PHI,DEL,PSI,HSUBP,TPROD,ERMAX,MAXITS,IER)      AFTP 790
C                                                                       AFTP 800
      RETURN                                                            AFTP 810
        END
```

```
C******************** VERSION 1.1 *** 8/01/74 ****************************
C
C     SUBROUTINE CLDPRD
C
C     PURPOSE:
C        TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HC-AIR
C        COMBUSTION AT TEMPERATURES AND PRESSURES WHERE DISSOCIATION
C        OF THE PRODUCT GASES MAY BE IGNORED.  THE DENSITY OF THE
C        PRODUCT GAS IS ALSO CALCULATED, AS ARE THE PARTIAL
C        DERIVATIVES OF BOTH OF THESE QUANTITIES WITH RESPECT TO
C        PRESSURE AND TEMPERATURE.
C
C     USAGE:
C        CALL CLDPRD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSUBT,RHO,DRHODT,
C                    DRHODP,IER)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE PRESSURE OF PRODUCTS (ATM)
C        T      - TEMPERATURE OF PRODUCTS (DEG K)
C        PHI    - EQUIVALENCE RATIO (FUEL/AIR RATIO DIVIDED BY THE
C                 CHEMICALLY CORRECT FUEL/AIR RATIO)
C        DEL    - MOLAR C:H RATIO OF THE PRODUCTS
C        PSI    - MOLAR N:O RATIO OF THE PRODUCTS
C      RETURNS:
C        ENTHLP- SPECIFIC ENTHALPY OF THE GAS (KCAL/G)
C        CSUBP - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T
C                AT CONSTANT P   (CAL/G-DEG K)
C        CSUBT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P
C                AT CONSTANT T   (CC/G)
C        RHO   - DENSITY OF THE MIXTURE (G/CC)
C        DRHODT- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT
C                CONSTANT P (G/CC-DEG K)
C        DRHODP- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT
C                CONSTANT T (G/CC-ATM)
```

```
C        IER    - FLAG, SET TO 1 FOR T<100 DEG K
C                          2 FOR T> 6000 DEG K
C                          0 OTHERWISE
C
C     REMARKS:
C        1)  ENTHALPY DATUM STATE IS AT T  =  0 ABSOLUTE WITH
C            O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
C        2) IN CASE OF PROBLEMS CONTACT MIKE MARTIN AT 253-2411
C           (ROOM 3-339 D)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED:  NONE
C
C     METHOD:
C        DESCRIBED IN APPENDIX IV OF WRITEUP
C
C*************************************************************************
      SUBROUTINE CLDPRD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSUBT,RHO,
     1 DRHODT,DRHODP,IER)
C
      LOGICAL RICH,LEAN
      DIMENSION A(6,6,2),X(6)
      DIMENSION A1(36),A2(36)
      EQUIVALENCE (A1(1),A(1,1,1)),(A2(1),A(1,1,2))
      REAL*4  MBAR,K
C
C        INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C        RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C        USED. FLAG TEMPERATURES TOO BIG OR TOO SMALL
C
      DATA A1/11.94033,2.088581,-0.47029,.037363,-.589447,-97.1418,
     1 6.139094,4.60783,-.9356009,.06669498,.0335801,-56.62588,
     2  7.099556,1.275957,-.2877457,.022356,-.1598696,-27.73464,
     3  5.555680,1.787191,-.2881342,.01951547,.1611828, .76498,
     4  7.865847,.6883719,-.031944,-.00268708,-.2013873,-.893455,
     5  6.807771,1.453404,-.328985,.02561035,-.1189462,-.331835/
```

```
      DATA A2/4.737305,16.65283,-11.23249,2.828001,.00676702,-93.75793,
     7 7.809672,-.2023519,3.418708,-1.179013,.00143629,-57.08004,
     8 6.97393,-.8238319,2.942042,-1.176239,.0004132409,-27.19597,
     9 6.991878,.1617044,-.2182071,.2968197,-.01625234,-.118189,
     & 6.295715,2.388387,-.0314788,-.3267433,.00435925,.103637,
     - 7.092199,-1.295825,3.20688,-1.202212,-.0003457938,-.013967/
C
      RICH = PHI .GT. 1.0
      LEAN =  .NOT. RICH
      EPS = 4.*DEL/(1. + 4.*DEL)
      IER = 0
      IF (T .LT. 100.) IER = 1
      IF (T .GT. 6000.) IER  =  2
      IR = 1
      IF (T .LT. 500.) IR = 2
C
C        GET THE COMPOSITION IN MOLES/MOLE OXYGEN
C
      IF (RICH)  GO TO 10
      X(1) = EPS*PHI
      X(2) = 2.*(1.- EPS)*PHI
      X(3) = 0.
      X(4) = 0.
      X(5) = 1.- PHI
      GO TO 20
   10 Z = 1000./T
      K = EXP(2.743 + Z*(-1.761 + Z*(-1.611 + Z*.2803)))
      ALPHA = 1. - K
      BETA = (2.*(1.- EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI))
      GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
      C = ( - BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(2.*ALPHA)
      X(1) = EPS*PHI - C
      X(2) = 2.*(1. - EPS*PHI) + C
      X(3) = C
      X(4) = 2.*(PHI - 1.) - C
```

```
      X(5) = 0.
   20 X(6) = PSI
C
C        CONVERT COMPOSITION TO MOLE FRACTIONS AND CALCULATE AVERAGE
C        MOLECULAR WEIGHT
C
      IF (LEAN) TMOLES = 1. + PSI + PHI*(1.-EPS)
      IF (RICH) TMOLES = PSI + PHI*(2.-EPS)
      DO 30 J = 1,6
   30    X(J) = X(J)/TMOLES
      MBAR = ((8.*EPS + 4.)*PHI + 32. + 28.*PSI)/TMOLES
C
C        CALCULATE H, CP, AND CT AS IN WRITEUP, USING FITTED
C        COEFFICIENTS FROM JANAF TABLES
C
      ENTHLP = 0.
      CSUBP = 0.
      CSUBT = 0.
      ST = T/1000.
      DO 40 J = 1,6
         TH = ((( A(4,J,IR)/4.*ST + A(3,J,IR)/3. )*ST
     1         + A(2,J,IR)/2. )*ST + A(1,J,IR) )*ST
         TCP = (( A(4,J,IR)*ST + A(3,J,IR) )*ST
     1               + A(2,J,IR) )*ST + A(1,J,IR)
         TH  =  TH - A(5,J,IR)/ST  +  A(6,J,IR)
         TCP  =  TCP  +   A(5,J,IR)/ST**2
         ENTHLP  =  ENTHLP  +  TH*X(J)
   40    CSUBP  =  CSUBP  +  TCP*X(J)
      ENTHLP = ENTHLP/MBAR
      CSUBP = CSUBP/MBAR
C
C        NOW CALCULATE RHO AND ITS PARTIAL DERIVATIVES
C        USING PERFECT GAS LAW
C
      RHO = .012187*MBAR*P/T
```

```
      DRHODT = -RHO/T                                                   CLDF1400
      DRHODF = RHO/F                                                    CLDF1410
C                                                                       CLDF1420
C        ALL DONE                                                       CLDF1430
      RETURN                                                            CLDF1440
        END
```

```
      SUBROUTINE DERIVS(P,T,PHI,EPS,PSI,A,X,Y,U,AMWT,CSUBP,CSUBT,
     1   DRHODT,DRHODP)
C
C     THIS ROUTINE EXISTS SOLELY FOR USE BY HPROD, MANY OF WHOSE
C     INTERNAL PARAMERERS IT USES.  IT IS ESSENTIALLY USELESS FOR ANY
C     OTHER PURPOSE.  THE EQUATIONS USED CAN BE FOUND IN APPENDIX II
C     OF THE WRITEUP
C
      LOGICAL RICH,LEAN
      DATA ROVR2/.99345/
      DATA SCALF/41.29287/
C
      RICH = PHI .GE. 1.0
      LEAN = .NOT. RICH
C
      C3 = (117. + 30.*EPS)*1000.
      C4 = 1.35E5*EPS
      C5 = 2.0 - EPS + PSI
      C6 = 5.0 - 2.*EPS + 2.*PSI
C
      DUDTPX = 6.3E4*U/T**2
      DUDPTX = -U/P
      DUDXPT = -U/(X*(1. - 2.*EPS*X))
C
      DADTP = (3.4E4*2./3.)*A/T**2
      DADPT = -A/(3.*P)
C
      AP = EPS*A
      T5 = 3.*C5
      DXDA = T5*(T5 + 2.*C6*AP)/(T5*(1. + 2.*AP) + 2.*C6*AP**2)**2
C
      Z = (1. - PHI)/X
      IF (LEAN) DYDX = (1. + .72*Z)/(1. + .36*Z)**2
      IF(RICH) DYDX = (1.- 1.28*Z + .90*Z**2)/(1.-.64*Z + .3*Z**2)**2
C
```

```
      DYDTP = DYDX*DXDA*DADTP
      DYDPT = DYDX*DXDA*DADPT
      DUDTP = DUDXPT*DXDA*DADTP + DUDTPX
      DUDPT = DUDXPT*DXDA*DADPT + DUDPTX
C
      DHFDPT = C3*DYDPT + C4*DUDPT
      DC2DPT = -2.*(3.*DYDPT + DUDPT)
      DC1DPT = 5.*DYDPT + 3.*DUDPT
      DHFDTP = C3 * DYDTP + C4*DUDTP
      DC2DTP = -2.*(3.*DYDTP + DUDTP)
      DC1DTP = 5.*DYDTP + 3.*DUDTP
C
      TVO = (3000. - 2000.*EPS + 300.*PSI)/(1. - .5*EPS + .09*PSI)
      EARG = EXP(TVO/T)
      TV = TVO/(EARG - 1.)
      DTVDTP = TVO*EARG/(T*(EARG - 1.))**2 *TVO
C
      AMCP = (8.*EPS + 4.)*PHI + 32. + 28.*PSI
      C1 = 7.*PSI + 5.*Y + 3.*U
      C2 = 2.*(PSI - 3.*Y - U)
      IF (LEAN) C1 = C1 + 7. + (9. - 8.*EPS)*PHI
      IF (RICH) C1 = C1 + 2. + 2.*(7. - 4.*EPS)*PHI
      IF (LEAN) C2 = C2 + 2.*(1. + (5. - 3.*EPS)*PHI)
      IF (RICH) C2 = C2 + 2.*(4. + (2. - 3.*EPS)*PHI)
C
      CSUBP = ROVR2/AMCP*(C1 + T*DC1DTP + C2*DTVDTP + TV*DC2DTP
     1                + DHFDTP)
      CSUBT = ROVR2/AMCP*(T*DC1DPT + TV*DC2DPT + DHFDPT)*SCALF
C
      IF (LEAN) G = 1. + (1.-EPS)*PHI + PSI + Y + U
      IF (RICH) G = (2.- EPS)*PHI + PSI + Y + U
      G = -AMCP/G**2
      DMDTP = G*(DYDTP + DUDTP)
      DMDPT = G*(DYDPT + DUDPT)
C
```

```
      DRHODT = .012187*P/T*(DMDTP - AMWT/T)                        DRVS 710
      DRHODP = .012187/T*(AMWT + P*DMDPT)                          DRVS 720
C                                                                  DRVS 730
      RETURN                                                       DRVS 740
        END
```

```
C****************** VERSION 1.0 *** 5/29/74 ****************************HPRD 010
C                                                                       HPRD 020
C     SUBROUTINE HPROD                                                  HPRD 030
C                                                                       HPRD 040
C     PURPOSE:                                                          HPRD 050
C        TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HYDRO-   HPRD 060
C        CARBON-AIR COMBUSTION AS A FUNCTION OF TEMPERATURE AND PRES-   HPRD 070
C        SURE, USING AN APPROXIMATE CORRECTION FOR DISSOCIATION.        HPRD 080
C        THE PARTIAL DERIVATIVES OF H WITH RESPECT TO THESE VARIABLES   HPRD 090
C        ARE ALSO CALCULATED, ALONG WITH THE GAS DENSITY AND ITS PAR-   HPRD 100
C        TIAL DERIVATIVES                                               HPRD 110
C                                                                       HPRD 120
C     USAGE:                                                            HPRD 130
C        CALL HPROD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSUBT,RHO,DRHODT,      HPRD 140
C                   DRHODP)                                             HPRD 150
C                                                                       HPRD 160
C     DESCRIPTION OF PARAMETERS:                                        HPRD 170
C      GIVEN:                                                           HPRD 180
C        P      - ABSOLUTE PRESSURE OF PRODUCTS (ATM)                   HPRD 190
C        T      - TEMPERATURE OF PRODUCTS (DEG K)                       HPRD 200
C        PHI    - EQUIVALENCE RATIO (FUEL/AIR RATIO DIVIDED BY THE      HPRD 210
C                 CHEMICALLY CORRECT FUEL/AIR RATIO)                    HPRD 220
C        DEL    - MOLAR C:H RATIO OF THE PRODUCTS                       HPRD 230
C        PSI    - MOLAR N:O RATIO OF THE PRODUCTS                       HPRD 240
C      RETURNS:                                                         HPRD 250
C        ENTHLP- SPECIFIC ENTHALPY OF THE PRODUCTS (KCAL/G)             HPRD 260
C        CSUBP - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T         HPRD 270
C                AT CONSTANT P   (CAL/G-DEG K)                          HPRD 280
C        CSUBT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P         HPRD 290
C                AT CONSTANT T   (CC/G)                                 HPRD 300
C        RHO   - DENSITY OF THE PRODUCTS        (G/CC)                  HPRD 310
C        DRHODT- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT         HPRD 320
C                CONSTANT P   (G/CC-DEG K)                              HPRD 330
C        DRHODP- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT         HPRD 340
C                CONSTANT T   (G/CC-ATM)                                HPRD 350
```

```
C
C     REMARKS:
C        1)  ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C            O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
C        2) IN CASE OF PROBLEMS CONTACT MIKE MARTIN AT 253-2411
C           (ROOM 3-339 D)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C            DERIVS,CLDPRD
C
C     METHOD:
C        SEE MARTIN & HEYWOOD 'APPROXIMATE RELATIONS FOR THE THERMO-
C        DYNAMIC PROPERTIES OF HYDROCARBON-AIR COMBUSTION PRODUCTS'
C
C***********************************************************************
C
      SUBROUTINE HPROD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSUBT,RHO,DRHODT,
     1    DRHODP)
      LOGICAL RICH,LEAN,NOTHOT,NOTWRM,NOTCLD
C
C     INITIALIZE PARAMETERS USED IN THE CALCULATION
C
      DATA AHFCO2,AHFH2O,AHFCO/-93.965,-57.103,-27.200/
      DATA ROVR2/.99345E-3/
      DATA TCOLD,THOT /1000.,1100./
C
      RICH = PHI .GE. 1.0
      LEAN = .NOT. RICH
      NOTHOT = T .LT. THOT
      NOTCLD = T .GT. TCOLD
      NOTWRM = .NOT. (NOTCLD .AND. NOTHOT)
      EPS=(4.*DEL)/(1. + 4.*DEL)
C
C     USE SIMPLE ROUTINE FOR LOW TEMPERATURE MIXES
C
```

```
      IF (NOTCLD) GO TO 5
      CALL CLDPRD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSUBT,RHO,DRHODT,
     1    DRHODP,IER)
      RETURN
C
C     CALCULATE EQUILIBRIUM CONSTANTS FOR DISSOCIATION
C     (NOTE THAT UNITS ARE INVERSE PRESSURE TO THE 1/2 POWER)
C
    5 AK1 = .39E-4 * EXP(-.3*EPS + 34000./T)
      AK2 = .14E-3 * EXP(1.3*EPS + 29000./T)
C
C     CALCULATE A, X, Y, AND U AS IN NOTES
C
      A = ((2.- EPS + PSI)/(4.*P*AK1*AK1))**(.33333333)
C
      T1 = 2.- EPS + PSI
      T2 = 1. + 2.*T1
      T3 = EPS*A
      X = A*(3.*T1 + T2*T3)/(3.*(1.+ 2.*T3)*T1 + 2.*T2*T3*T3)
C
      Z = (1.- PHI)/X
      IF (RICH)  Y = X/(1.- .64*Z + .30*Z**2)
      IF (LEAN)  Y = X*(1.+ Z + .36*Z**2)/(1. + .36*Z) - (1. - PHI)
      U = (2. - EPS + PSI)*(1.- 2.*EPS*X)/(4.*AK1*AK2*P*X)
C
C     CALCULATE THE ENTHALPY OF FORMATION FOR THIS APPROXIMATE
C     COMPOSITION
C
      ENTFOR = 1000.*ROVR2*((117. + 30.*EPS)*Y + 135.*EPS*U)
      XH2O = 2.*(1.- EPS)*PHI
      T1 = 7.*PSI + 5.*Y + 3.*U
      T2 = PSI - 3.*Y - U
C
      IF (LEAN)  GO TO 10
C
```

```
      RCVT = 2. + 2.*(7. - 4.*EPS)*PHI + T1
      RCVV = 4. + (2.- 3.*EPS)*PHI + T2
      XCO2 = 2.- (2.- EPS)*PHI
      XCO = 2.*(PHI - 1.)
      ENTFOR = ENTFOR - 1000.*ROVR2*6.5*(PHI - 1.)/EPS
      GO TO 20
C
   10 RCVT = 7. + (9. - 8.*EPS)*PHI + T1
      RCVV = 1. + (5.- 3.*EPS)*PHI + T2
      XCO = 0.
      XCO2 = EPS*PHI
C
   20 ENTFOR = ENTFOR + (XCO2*AHFCO2 + XH2O*AHFH2O + XCO*AHFCO)
C
C     ADD IN TRANSLATIONAL,VIBRATIONAL, AND ROTATIONAL TERMS TO GET
C     TOTAL ENTHALPY
C
      TV = (3000.- 2000.*EPS + 300.*PSI)/(1.- .5*EPS + .09*PSI)
      TV = TV/( EXP(TV/T) - 1.)
      AMCP = (8.*EPS + 4.)*PHI + 32. + 28.*PSI
C
      ENTHLP = (ROVR2*(RCVT*T + RCVV*TV*2.) + ENTFOR)/AMCP
C
C     CALCULATE AVERAGE MOLECULAR WEIGHT, AND GET DENSITY BY
C     USING THE PERFECT GAS LAW
C
      IF (LEAN)  AMWT = AMCP/(1. + (1.- EPS)*PHI + PSI + Y + U)
      IF (RICH)  AMWT = AMCP/((2.- EPS)*PHI + PSI + Y + U)
      RHO = .012187*AMWT*P/T
C
C     GET PARTIAL DERIVATIVES BY WAY OF A SUBROUTINE CALL
C
      CALL DERIVS(P,T,PHI,EPS,PSI,A,X,Y,U,AMWT,CSUBP,CSUBT,DRHODT,
     1   DRHODP)
C
```

```
C
C     IF CALCULATING FOR AN INTERMEDIATE TEMPERATURE, USE A WEIGHTED
C     AVERAGE OF THE RESULTS FROM THIS ROUTINE AND THOSE FROM THE
C     SIMPLE ROUTINE
C
      IF (NOTWRM) RETURN
C
      CALL CLDPRD(P,T,PHI,DEL,PSI,TH,TCP,TCT,TRHO,TDRT,TDRP,IER)
      W1 = (T - TCOLD)/(THOT - TCOLD)
      W2 = 1.0 - W1
C
      ENTHLP = W1*ENTHLP + W2*TH
      CSUBP = W1*CSUBP + W2*TCP
      CSUBT = W1*CSUBT + W2*TCT
      RHO = W1*RHO + W2*TRHO
      DRHODT = W1*DRHODT + W2*TDRT
      DRHODP = W1*DRHODP + W2*TDRP
C
      RETURN
        END
```

```
C******************** VERSION 1.0 *** 5/29/74 ***************************
C     SUBROUTINE TEMP
C
C     PURPOSE:
C        TO CALCULATE THE TEMPERATURE OF THE PRODUCTS OF HC-AIR
C        COMBUSTION, FOR GIVEN SPECIFIC ENTHALPY OF THE PRODUCTS, AND
C        FOR GIVEN ABSOLUTE PRESSURE
C
C     USAGE:
C        CALL TEMP(P,TGUESS,PHI,DEL,PSI,ENTHLP,T,ERMAX,MAXITS,IER)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE PRESSURE OF THE PRODUCTS (ATM)
C        TGUESS- INITIAL GUESS FOR T (DEG K)
C        PHI    - EQUIVALENCE RATIO OF THE PRODUCTS
C        DEL    - MOLAR C:H RATIO OF THE PRODUCTS
C        PSI    - MOLAR N:O RATIO OF THE PRODUCTS
C        ENTHLP-  ENTHALPY OF THE PRODUCTS (KCAL/G)
C        ERMAX - MAXIMUM ALLOWABLE RELATIVE ERROR IN RESULTANT T
C        MAXITS- MAXIMUM NUMBER OF ALLOWABLE ITERATIONS WITHOUT
C                SUCCESS
C        IER    - FLAG, SET TO 1 IF NO SUCCESS WITHIN MAXITS ITERATIONS
C      RETURNS:
C        T      - TEMPERATURE OF THE PRODUCTS  (DEG K)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C        HPROD
C
C     METHOD:
C        NEWTON-RAPHSON ITERATION
C
C***********************************************************************
      SUBROUTINE TEMP(P,TGUESS,PHI,DEL,PSI,ENTHLP,T,ERMAX,MAXITS,IER)
      T = TGUESS
```

```
      IER = 0
C
      DO 10 I = 1,MAXITS
         CALL HPROD(P,T,PHI,DEL,PSI,AHG,CSUBP,CSUBT,RHO,DRHODT,DRHODP)
         TOLD = T
         T = T + (ENTHLP - AHG)/(CSUBP * 1.0E-3)
         IF( ABS((T - TOLD)/ T)  .LE. ERMAX) GO TO 20
   10 CONTINUE
C
      IER = 1
   20 RETURN
        END
```

```
C****************** VERSION 1.0 *** 11/13/74 ***************************
C
C     FUNCTION TSUBU2
C
C     PURPOSE:
C        TO CALCULATE THE TEMPERATURE OF UNBURNED CHARGE IN A TCCS
C         STRATIFIED CHARGE ENGINE FOLLOWING AN ISENTROPIC EXPANSION
C         OR COMPRESSION
C
C     USAGE:
C        TEMPU = TSUBU2 (P, PNOT, TNOT, EMAX)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE PRESSURE (ATM) AT END OF PROCESS
C        PNOT   - ABSOLUTE PRESSURE (ATM) AT START OF PROCESS
C        TNOT   - ABSOLUTE TEMPERATURE (DEG K) AT START OF PROCESS
C        EMAX   - MAXIMUM ALLOWABLE RELATIVE ERROR IN TSUBU2
C      GIVEN IN COMMON AREA /CHARGE/ :
C        PHI    - AVERAGE EQUIVALENCE RATIO OF THE RESIDUAL
C        DEL    - MOLAR C:H RATIO OF THE FUEL
C        PSI    - MOLAR N:O RATIO OF THE CHARGE (APPROX 3.76 FOR AIR)
C        RESFRK- MASS FRACTION OF THE CHARGE THAT IS RESIDUAL
C        CHMASS- TOTAL MASS OF CHARGE (GRAMS)
C        QLOWER- LOWER HEATING VALUE OF THE FUEL (KCAL/G) AT 293 DEG K
C        CFUEL - SPECIFIC HEAT AT CONSTANT PRESSURE (CAL/G-DEG K) OF
C                THE FUEL VAPOR
C
C      RETURNS:
C        TSUBU2 - FINAL TEMPERATURE (DEG K)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C        UPROP2
C
C     REMARKS:
```

```
C         1) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
C            OR ROOM 3-339D
C
C     METHOD:
C          ADAPTIVE PREDICTOR-CORRECTOR METHOD
C
C*************************************************************************
      FUNCTION TSUBU2 (F, FNOT, TNOT, EMAX)
      COMMON /CHARGE/ PHI, DEL, PSI, RESFRK, CHMASS, QLOWER, CFUEL
C
      DATA FSCALE /2.42173E-2/
C
      LOGICAL DONE
      DONE = .FALSE.
C
C     INITIALIZE PARAMETER VALUES
C
      TSUBU2 = TNOT
      IF (F .EQ. FNOT)  RETURN
      DELF = SIGN(.1, F - FNOT)
      FOLD = FNOT
      TOLD = TNOT
      EMIN = EMAX/10.
C
C     CHECK STEPSIZE
C
   10 IF (ABS(F - FOLD) .GT. ABS(DELF))  GO TO 20
C
C     IF TOO BIG, REDUCE AND SIGNAL DONE
C
      DELF = F - FOLD
      DONE = .TRUE.
C
C     DO PREDICTOR-CORRECTOR
C
```

```
 20 CALL UPROP2 (FOLD, TOLD, PHI, DEL, PSI, RESFRK, XH, CP, CT, RHO,
   *              RT, RP)
    G1    = (1./RHO - CT)/CP
    TSTAR = TOLD + DELP*G1*PSCALE
    PNEW  = POLD + DELP
    CALL UPROP2 (PNEW, TSTAR, PHI, DEL, PSI, RESFRK, XH, CP, CT, RHO,
   *              RT, RP)
    G2    = (1./RHO - CT)/CP
    TNEW  = TOLD + DELP*PSCALE*(G1 + G2)/2.
    ERROR = ABS((TNEW - TSTAR)/TNEW)
C
C     IF ERROR TOO LARGE, CHANGE STEPSIZE
C
    IF (ERROR .LT. EMAX) GO TO 30
    DONE = .FALSE.
    DELP = DELP*.8
    GO TO 20
C
C     OTHERWISE, UPDATE P AND T
C
 30 POLD = PNEW
    TOLD = TNEW
    IF (DONE)  GO TO 40
C
C     SEE IF ERROR TOO SMALL TO JUSTIFY THIS STEPSIZE
C
    IF (ERROR .GE. EMIN)  GO TO 10
C
C     IF SO, INCREASE STEPSIZE
C
    DELP = DELP*1.25
    GO TO 10
 40 TSUBU2 = TOLD
    RETURN
      END
```

```
C******************** VERSION 1.0 *** 11/13/74 ***************************
C
C     SUBROUTINE UPROP2
C
C        TO CALCULATE THE ENTHALPY AND DENSITY OF A HOMOGENOUS MIXTURE
C        OF AIR AND RESIDUAL GAS AS A FUNCTION OF TEMPERATURE AND
C        PRESSURE FOR GIVEN EQUIVALENCE RATIO OF THE RESIDUAL
C
C     USAGE:
C        CALL UPROP2 (P, T, PHI, DEL, PSI, RESFRK, ENTHLP, CSUBP, CSUBT,
C                     RHO, DRHODT, DRHODP)
C
C     DESCRIPTION OF PARAMETERS:
C      GIVEN:
C        P      - ABSOLUTE PRESSURE OF MIX (ATM)
C        T      - TEMPERATURE OF MIX (DEG K)
C        PHI    - EQUIVALENCE RATIO OF THE RESIDUAL GAS
C        DEL    - MOLAR C:H RATIO OF THE RESIDUAL GAS
C        PSI    - MOLAR N:O RATIO OF THE MIX
C      RETURNS:
C        ENTHLP- SPECIFIC ENTHALPY OF THE MIX (KCAL/G)
C        CSUBP - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T
C                AT CONSTANT P   (CAL/G-DEG K)
C        CSUBT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P
C                AT CONSTANT T   (CC/G)
C        RHO   - DENSITY OF THE PRODUCTS      (G/CC)
C        DRHODT- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT
C                CONSTANT P   (G/CC-DEG K)
C        DRHODP- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT
C                CONSTANT T   (G/CC-ATM)
C
C     REMARKS:
C        1)  ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C            O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
C        2) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
```

```
C          (ROOM 3-339 D)
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED:  NONE
C
C    METHOD:
C        ZERO ORDER EQUILIBRIUM MODEL (MAJOR SPECIES ONLY)
C
C**********************************************************************
      SUBROUTINE UPROP2 (P, T, PHI, DEL, PSI, RESFRK, ENTHLP, CSUBP,
     *                   CSUBT, RHO, DRHODT, DRHODP)
      LOGICAL   RICH,LEAN
      DIMENSION A(6,6,2), X(6)
      DIMENSION A1(36), A2(36)
      EQUIVALENCE (A1(1),A(1,1,1)), (A2(1),A(1,1,2))
      REAL  MBAR,K
C
C        INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C        RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C        USED. FLAG TEMPERATURES TOO BIG OR TOO SMALL
C
      DATA A1/11.94033, 2.088581, -0.47029, .037363, -.589447, -97.1418,
     1 6.139094, 4.60783, -.9356009, .06669498, .0335801, -56.62588,
     2  7.099556, 1.275957, -.2877457, .022356, -.1598696, -27.73464,
     3  5.555680, 1.787191, -.2881342, .01951547, .1611826,  .76498,
     4  7.865847, .6883719, -.031944, -.00268708, -.2013873, -.893455,
     5  6.807771, 1.453404, -.328985, .02561035, -.1189462, -.331835/
      DATA A2/4.737305, 16.65283, -11.2325, 2.828, .00676702, -93.75793,
     7  7.809672, -.2023519, 3.418708, -1.179013, .00143629, -57.08004,
     8  6.97393, -.8238319, 2.942042, -1.176239, .0004132409, -27.19597,
     9  6.991878, .1617044, -.2182071, .2968197, -.01625234, -.118189,
     &  6.295715, 2.388387, -.0314788, -.3267433, .00435925, .103637,
     -  7.092199, -1.295825, 3.20688, -1.202212, -.0003457938, -.013967/
C
      RICH = PHI .GT. 1.0
      LEAN = .NOT. RICH
```

```
      EPS   = 4.*DEL/(1. + 4.*DEL)
      IER   = 0
      IF (T .LT. 100.)  IER = 1
      IF (T .GT. 6000.) IER = 2
      IR = 1
      IF (T .LT. 500.) IR = 2
C
C        GET THE COMPOSITION IN MOLES/MOLE OXYGEN
C
      FCTRES = RESFRK
      FCTNEW = 1.0 - RESFRK
      IF (RICH) GO TO 10
C
      X(1) = EPS*PHI*FCTRES
      X(2) = 2.*(1.0 - EPS)*PHI*FCTRES
      X(3) = 0.
      X(4) = 0.
      X(5) = (1. - PHI)*FCTRES + FCTNEW
      GO TO 20
C
   10 Z     = 1000./T
      K     = EXP(2.743 + Z*(-1.761 + Z*(-1.611 + Z*.2803)))
      ALPHA = 1.0 - K
      BETA  = 2.*(1.- EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI)
      GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
      C     = (-BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(2.*ALPHA)
      X(1) = (EPS*PHI - C)*FCTRES
      X(2) = (2.0*(1. - EPS*PHI) + C)*FCTRES
      X(3) = C*FCTRES
      X(4) = (2.0*(PHI - 1.) - C)*FCTRES
      X(5) = FCTNEW
   20 X(6) = PSI
C
C        CONVERT COMPOSITION TO MOLE FRACTIONS AND CALCULATE AVERAGE
C        MOLECULAR WEIGHT
```

```
C
      IF (LEAN) TMOLES = PSI + PCTNEW + PCTRES*(1. + PHI*(1.-EPS))
      IF (RICH) TMOLES = PSI + PCTNEW + PCTRES*( PHI*(2. - EPS))
      DO 30 J = 1, 6
         X(J) = X(J)/TMOLES
   30 CONTINUE
      MBAR = ((8.*EPS + 4.)*PHI + 32. + 28.*PSI)/TMOLES
C
C        CALCULATE H, CP, AND CT AS IN WRITEUP, USING FITTED
C        COEFFICIENTS FROM JANAF TABLES
C
      ENTHLP = 0.
      CSUBP  = 0.
      CSUBT  = 0.
      ST     = T/1000.
      DO 40 J = 1, 6
         TH     = ((( A(4,J,IR)/4.*ST + A(3,J,IR)/3. )*ST
     1             +   A(2,J,IR)/2.)*ST + A(1,J,IR)   )*ST
         TCP    = (( A(4,J,IR)*ST + A(3,J,IR) )*ST
     1              + A(2,J,IR))*ST + A(1,J,IR)
         TH     =  TH - A(5,J,IR)/ST  +  A(6,J,IR)
         TCP    =  TCP  +   A(5,J,IR)/(ST*ST)
         ENTHLP =  ENTHLP +  TH*X(J)
         CSUBP  =  CSUBP  +  TCP*X(J)
   40 CONTINUE
      ENTHLP = ENTHLP/MBAR
      CSUBP  = CSUBP/MBAR
C
C        NOW CALCULATE RHO AND ITS PARTIAL DERIVATIVES
C        USING PERFECT GAS LAW
C
      RHO    = .012187*MBAR*P/T
      DRHODT = -RHO/T
      DRHODP = RHO/P
C
```

```
C           ALL DONE
      RETURN
      END
```

Table 1

Engine Specifications

DIMENSIONS*

bore	3.875 in.
stroke	3.875 in.
connecting rod	6.625 in.
clearance volume	4.570 $in.^3$

VALVE TIMINGS

	OPENS		CLOSES	
inlet valve	10 BTDC	(1)	55 ABDC	(2)
	0	(2)	45	(1)
exhaust valve	55 BBDC	(1)	10 ATDC	(2)
	45	(2)	0	(1)

(1) at 0.006 in. valve lift (2) valve face flush with head

* defined in Figure ( ) and Appendix B of ( )

Table 2

Injection System

PUMP

pump:	APE - B Bosch
cam:	6/1
plunger:	7mm.
reaction valve:	20 mm^3

NOZZLE

nozzle:	Roosa-Master XNM 1029
orifice diameter	.023 in.
orifice L/D	1.0
nozzle cracking pressure	2000
needle lift	.010 in.

Table 3

Summary of Instrumentation

Temperatures

Air Orifice Inlet	Water Outlet	Bearing Oil
Air Inlet	Exhaust	Fuel Inlet
Water Inlet	Crankcase Oil	Fuel Returns

Instrument - All Points

Chromel - Alumel Thermocouple

Omega DS - 500 Digital Readout

Resolution $1^{o}F$

Pressures

	Method	Resolution
Inlet Air	Water Manometer	.1 in.
Crankcase Vacuum	Water Manometer	.1 in.
Oil Pressure	Panel Gage	2 PSI
Exhaust	Mercury Manometer	.1 in.
Dynamometer Load	Mercury Manometer	.1 in.
Injection Line	Kistler 601 Piezoelectric transducer, Kistler 504E Charge Amplifier	30 PSI*
Combustion Chamber	Kistler 609A Piezoelectric Transducer, Kistler 503D Charge Amplifier	.2 PSI**

Table 3 (cont)

Flow Rates

	Method	Resolution
Air Inlet	ASME Square Edged Orifice with water manometers	0.05 g/sec
Fuel	Laboratory Scale and Timer	0.01 g/sec
Cooling Water	Rotameter	.2 lbm/sec
Position		
Crankangle	Trump Ross Rotary Pulse Generator 720 pulses per revolution plus Marker	.2 CA^o
Fuel Injector Needle Lift	AVL NH1 - 100 B LDT	1 μm

Gas Analysis Cart

Exhaust	
Hydrocarbons	Scott Model 215 FID HC Analyzer
Nitric Oxides	TELCO Model 10 A Chemilumenscent NO Analyzer
Carbon Dioxide	Beckman Model 315A NDIR CO_2 Analyzer
Carbon Monoxide	Beckman Model 315A NDIR CO Analyzer
Oxygen	Scott Model 150 Paramagnetic O_2 Analyzer

* Accuracy is effectively limited by the system transfer function and the 565 oscilloscope.

** See Text

Table 4

Summary of Fuel Properties

	Methanol CH_3OH	Iso-Octane C_8H_{18}	Cross-cut Distillate
Molecular Wt.	32	114	∿125
H:C Ratio	4:0	2.25	1.828
Specific Gravity	.796	.692	.80
Boiling Point ^{o}F	149	211	(106-648)
Lower Heating Value (Btu/lbm)	8580	19080	18038
Stoichiometric F/A Ratio	0.155	0.0665	0.0692
FIA - %			
Aromatics			29.5
Olefins			3.0
Saturates			67.5
Octane No. RON	106	100	76.6
Cetane No.			28.3

Table 5

Engine Operating Conditions for Emission Results

RPM	ϕ	θ_s	IMEP	ISFC
1500	0.759	-24	104.7	0.384
	0.625	-23	93.2	0.358
	0.446	-23	81.9	0.290
	0.278	-23	56.8	0.284
	0.261	-23	53.6	0.263
	0.172	-23	39.1	0.249
	0.143	-20	24.7	0.331
	0.113	-23	17.5	0.379
2000	0.828	-26	122.2	0.353
	0.650	-26	108.9	0.320
	0.475	-26	91.3	0.289
	0.348	-24	73.1	0.269
	0.218	-23	44.2	0.285
	0.161	-24	25.9	0.362
2500	0.811	-29	130.3	0.349
	0.639	-28	119.3	0.349
	0.524	-28	105.4	0.286
	0.371	-28	82.0	0.262
	0.249	-28	55.5	0.265
	0.193	-28	38.1	0.306
	0.124	-28	21.7	0.344

θ_s = Start of Injection

Ignition Always Preceeded by 2 CA^o

Table 5 (con't)

Cross Cut Distillate

RPM	ϕ	θ_s	IMEP	ISFC
1500	0.924	-22	112.1	0.432
	0.762	-20	105.4	0.392
	0.600	-20	93.0	0.358
	0.442	-19	79.7	0.299
	0.426	-20	76.3	0.317
	0.282	-19	55.5	0.284
	0.211	-19	41.3	0.290
	0.129	-18	22.8	0.327
2000	0.927	-25	112.9	0.416
	0.859	-23	112.4	0.390
	0.692	-23	98.5	0.372
	0.472	-23	88.4	0.296
	0.334	-23	63.6	0.303
	0.258	-23	51.4	0.290
	0.180	-23	34.9	0.304
	0.184	-20	32.4	0.338
2500	1.000	-26	122.5	0.439
	.850	-26	120.7	0.391
	.685	-25	108.9	0.353
	.546	-26	95.6	0.324
	.367	-25	69.3	0.303
	.291	-26	56.6	0.300
	.212	-23	39.7	0.314
	.218	-20	19.4	0.387

Table 5 (cont)

Methanol

RPM	ϕ	θ_s	IMEP	ISFC
1500	0.767	-25	106.9	0.878
	0.636	-28	101.7	0.755
	0.486	-26	89.0	0.676
	0.394	-26	77.7	0.637
	0.324	-26	66.4	0.616
	0.261	-24	50.8	0.655
	0.219	-24	40.7	0.697
2000	0.811	-28	108.9	0.900
	0.741	-28	106.9	0.838
	0.654	-28	104.6	0.766
	0.591	-28	100.5	0.731
	0.504	-28	92.7	0.682
	0.414	-28	84.6	0.632
	0.364	-25	72.5	0.643
	0.291	-25	58.6	0.640
	0.221	-25	26.9	1.077
2500	0.696	-35	106.3	0.824
	0.641	-35	102.3	0.795

Table 6

Matrix of Averaged Pressure Crankangle

Iso-Octane

RPM	ϕ_e	ϕ_e	$IMEP_m$	$IMEP_i$	θ_{is}	θ_{ie}	θ_{bs}	θ_{be}
1500	0.77	0.76	104.7	106.6	-24	9	-12	35
	0.46	0.45	81.9	82.3	-23	0	-13	35
	0.29	0.28	56.8	60.0	-23	-3	-12	24
2000	0.83	0.83	122.2	118.3	-25	13	-12	28
	0.49	0.48	91.3	88.5	-24	3	-9	24
	0.22	0.22	44.2	44.3	-23	-5	-7	23
2500	0.78	0.81	130.3	122.4	-29	15	-8	30
	0.52	0.52	105.4	99.6	-28	7	-9	30
	0.25	0.25	55.4	47.4	-28	-4	-9	29

Subscript Nomenclature

o = Observed from fuel air flow

e = Measured from exhaust gas composition

M = Dynamometer measurement

i = Integrated average pressure data

is = Injection start

ie = Injection end

bs = Start of heat release from Log P Log V plots

be = End of effective heat release from Log P Log plots

Table 6 (cont)

Cross Cut Distillate

RPM	ϕ_o	ϕ_e	$IMEP_M$	$IMEP_i$	θ_{is}	θ_{ie}	θ_{bs}	θ_{be}
1500	0.76	0.78	105.4	99.2	-20	10	-11	35
	0.43	0.43	76.3	73.3	-20	4	-13	36
	0.27	0.27	51.4	47.2	-20	-5	-11	35
2000	0.87	0.85	121.0	114.6	-24	15	-14	29
	0.49	0.47	88.4	84.9	-23	-2	-14	26
	0.26	0.26	51.4	46.5	-23	-12	-15	31
2500	0.83	0.82	121.3	124.8	-26	15	-14	31
	0.52	0.50	95.0	100.1	-26	0	-14	24
	0.29	0.28	56.1	59.7	-26	-9	-13	26

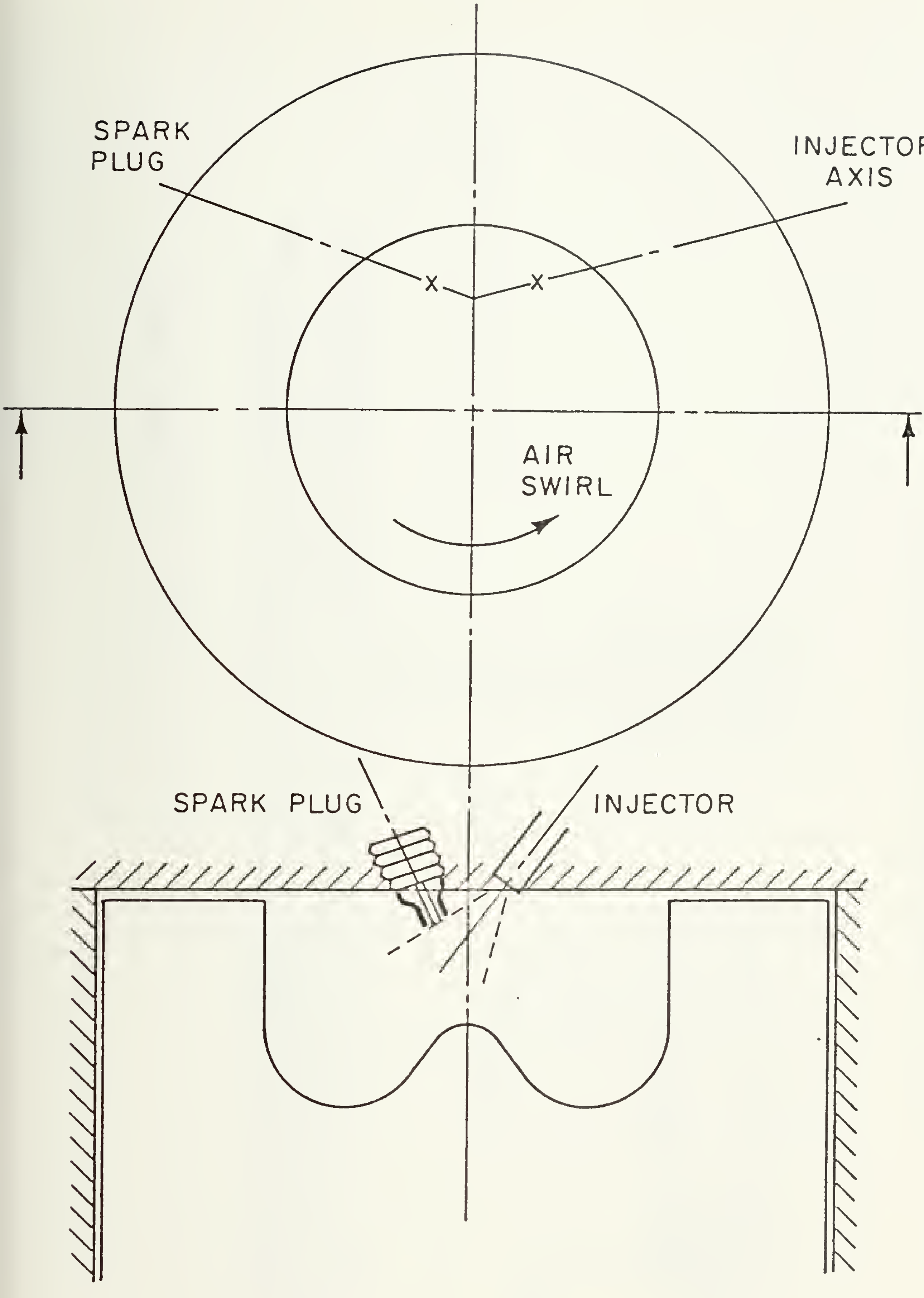


FIG. 1 -TEXACO CONTROLLED COMBUSTION SYSTEM (SCHEMATIC)

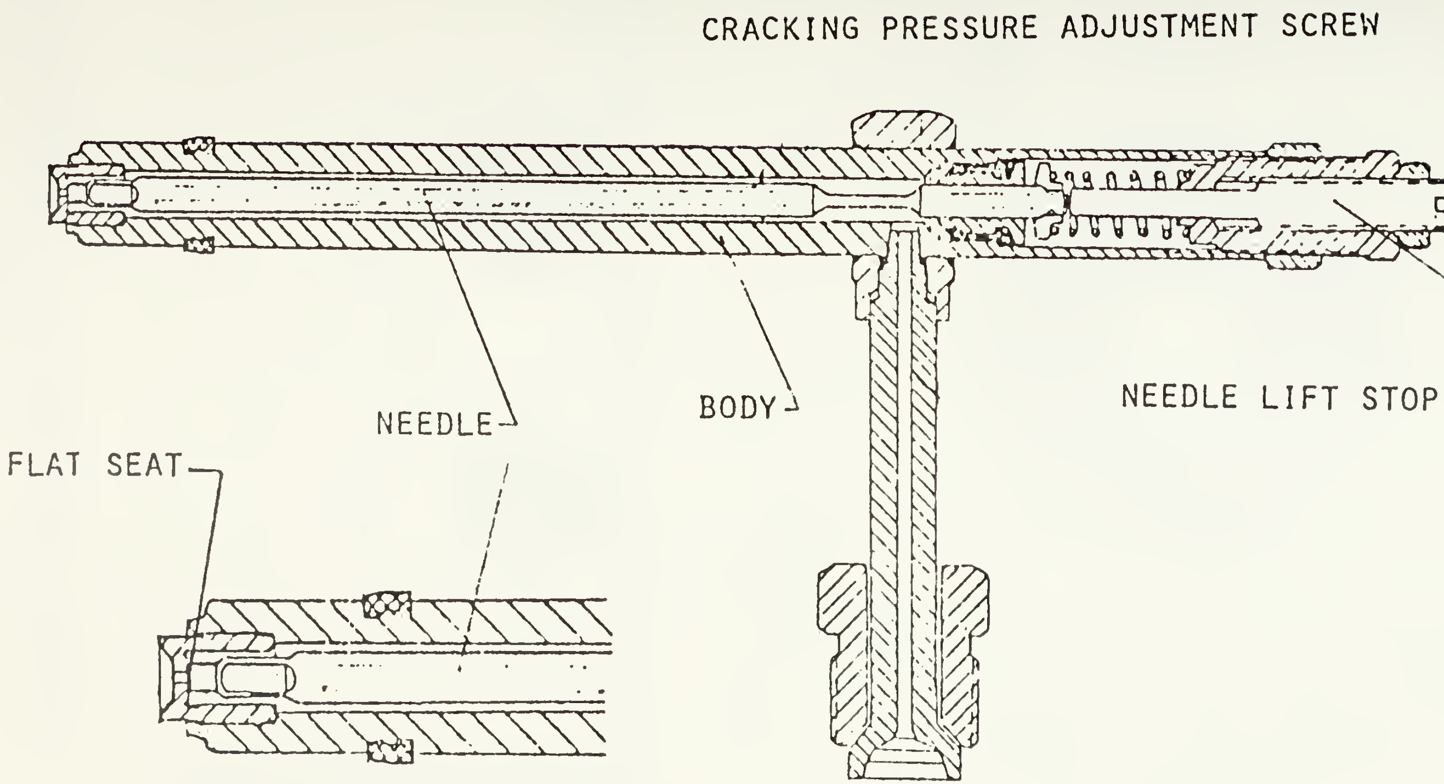
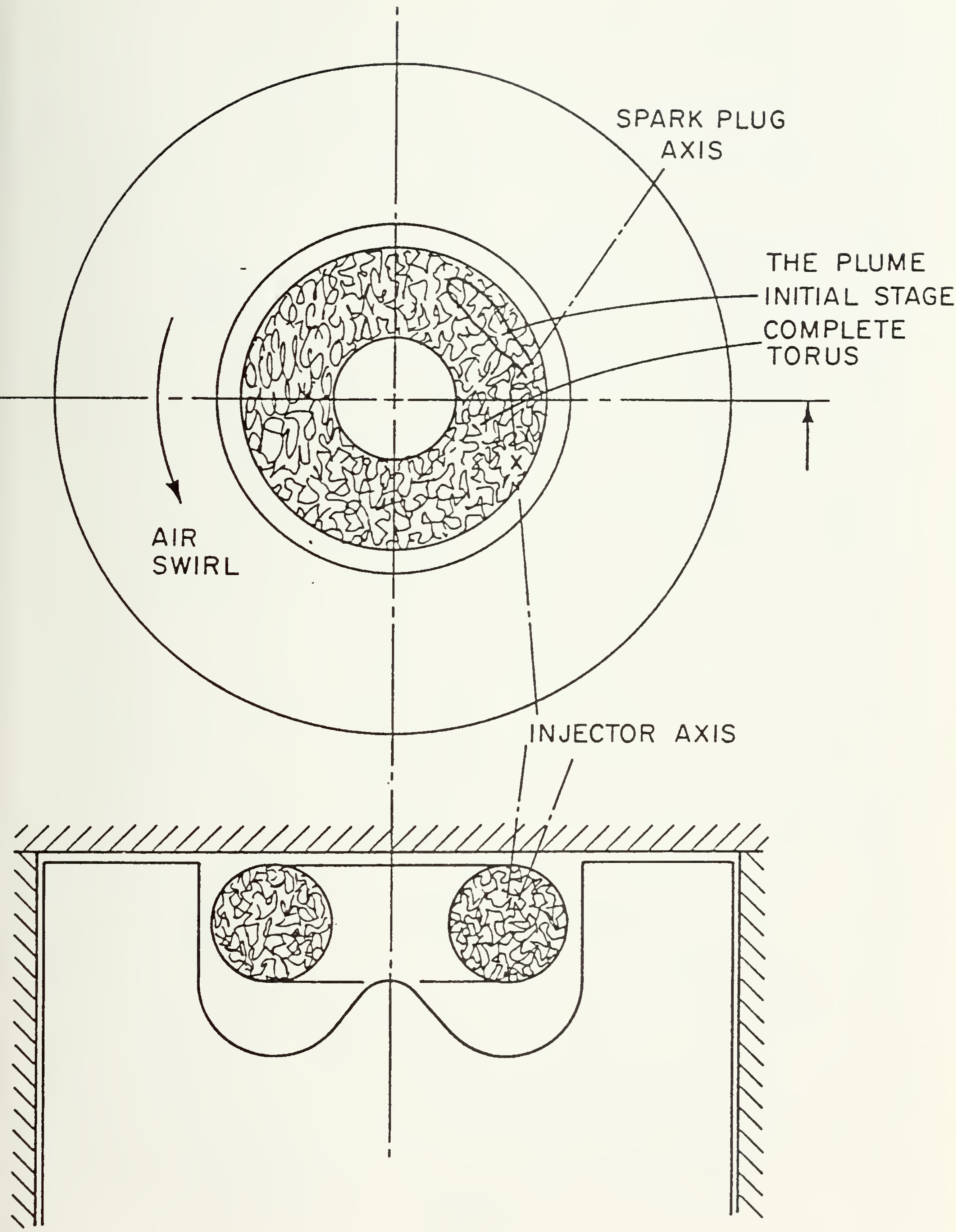


FIG. 2 ROOSA-MASTER INJECTION NOZZLE



SCHEMATIC OF THE COMBUSTION PROCESS

FIG. 3

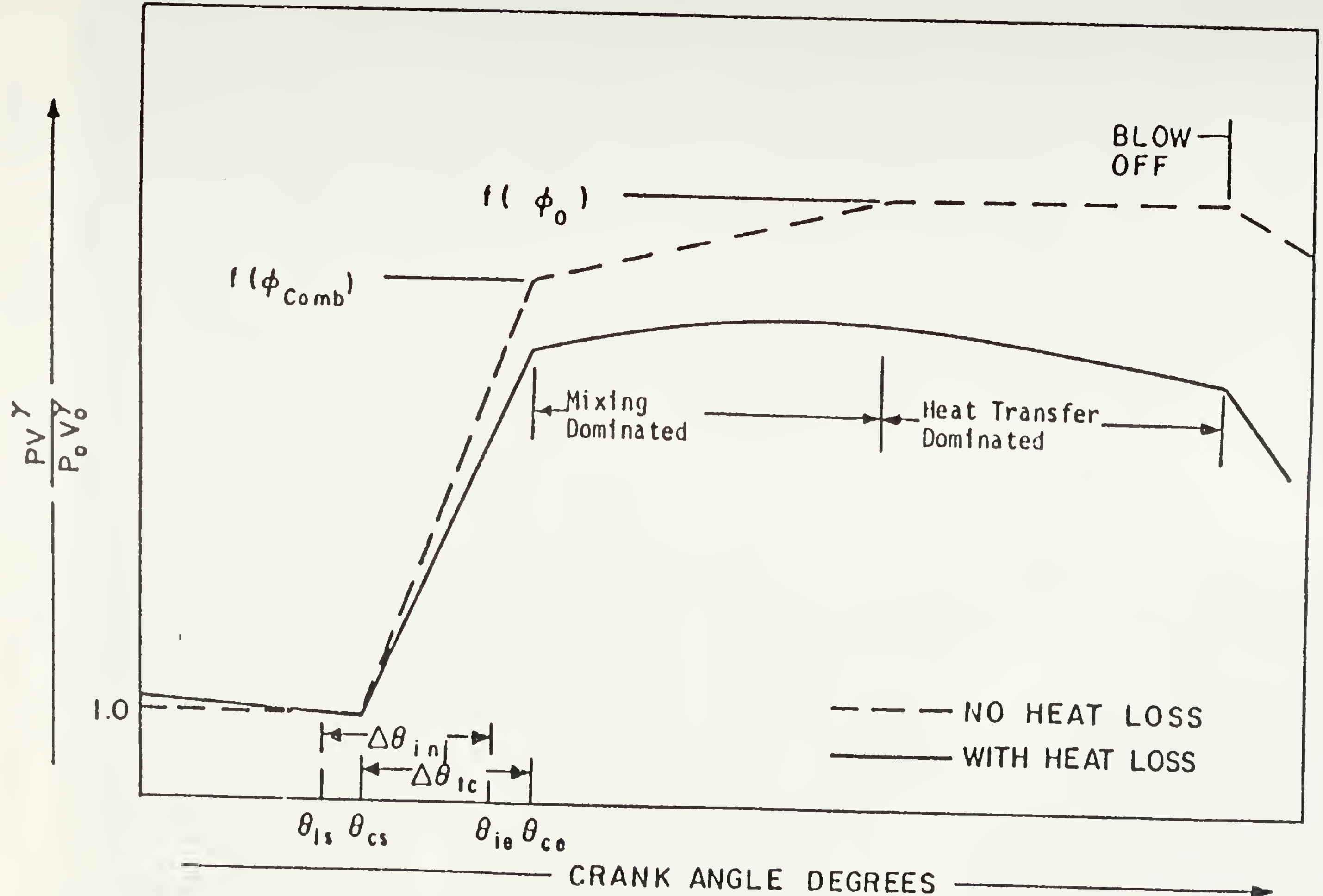


FIG. 4 Simplified PV^{γ} plot (Theory). $\Delta\theta_{inj}$ and $\Delta\theta_{rc}$ are injection and rapid combustion durations respectively.

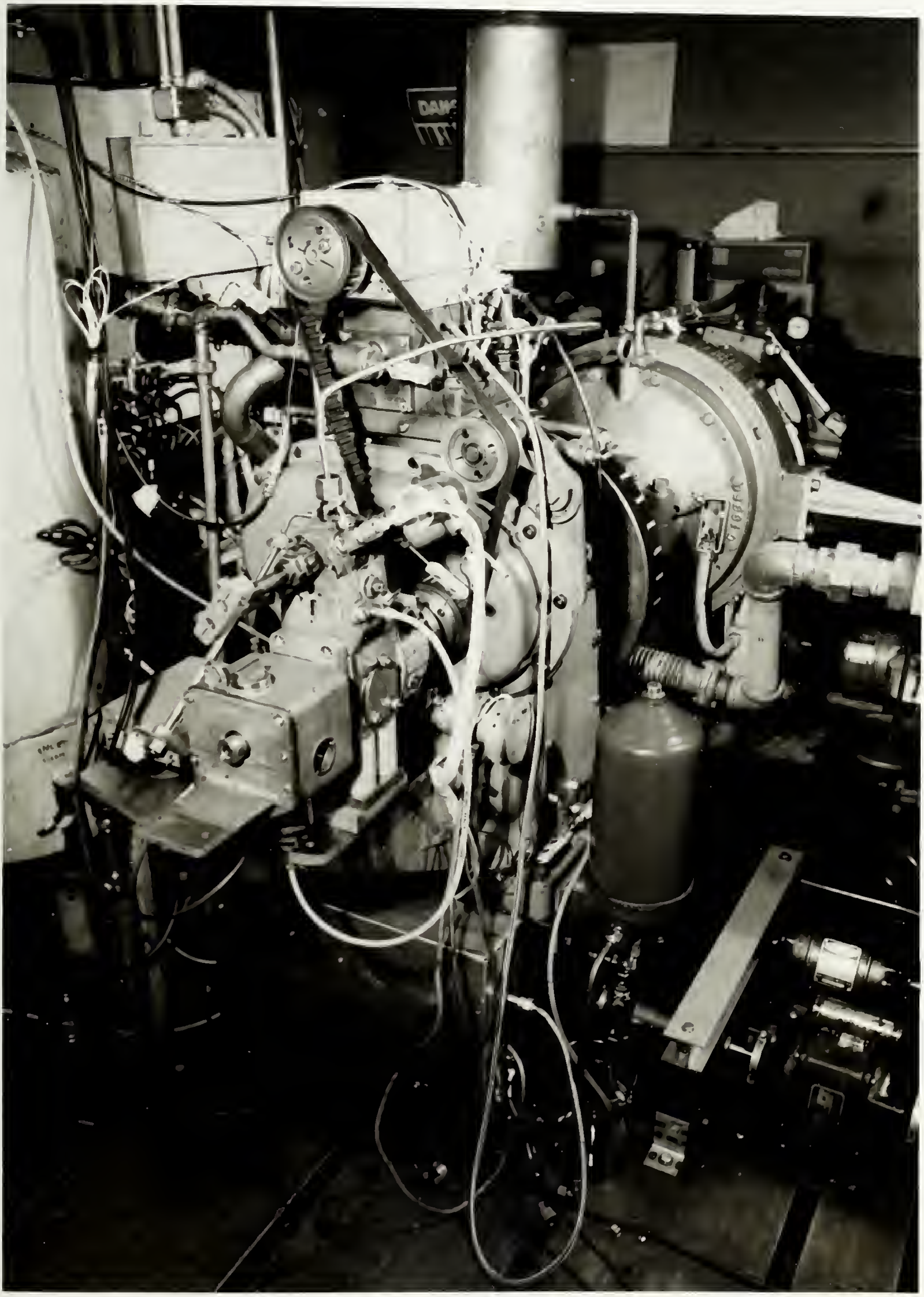


FIGURE 5 PHOTOGRAPH OF TEST INSTALLATION

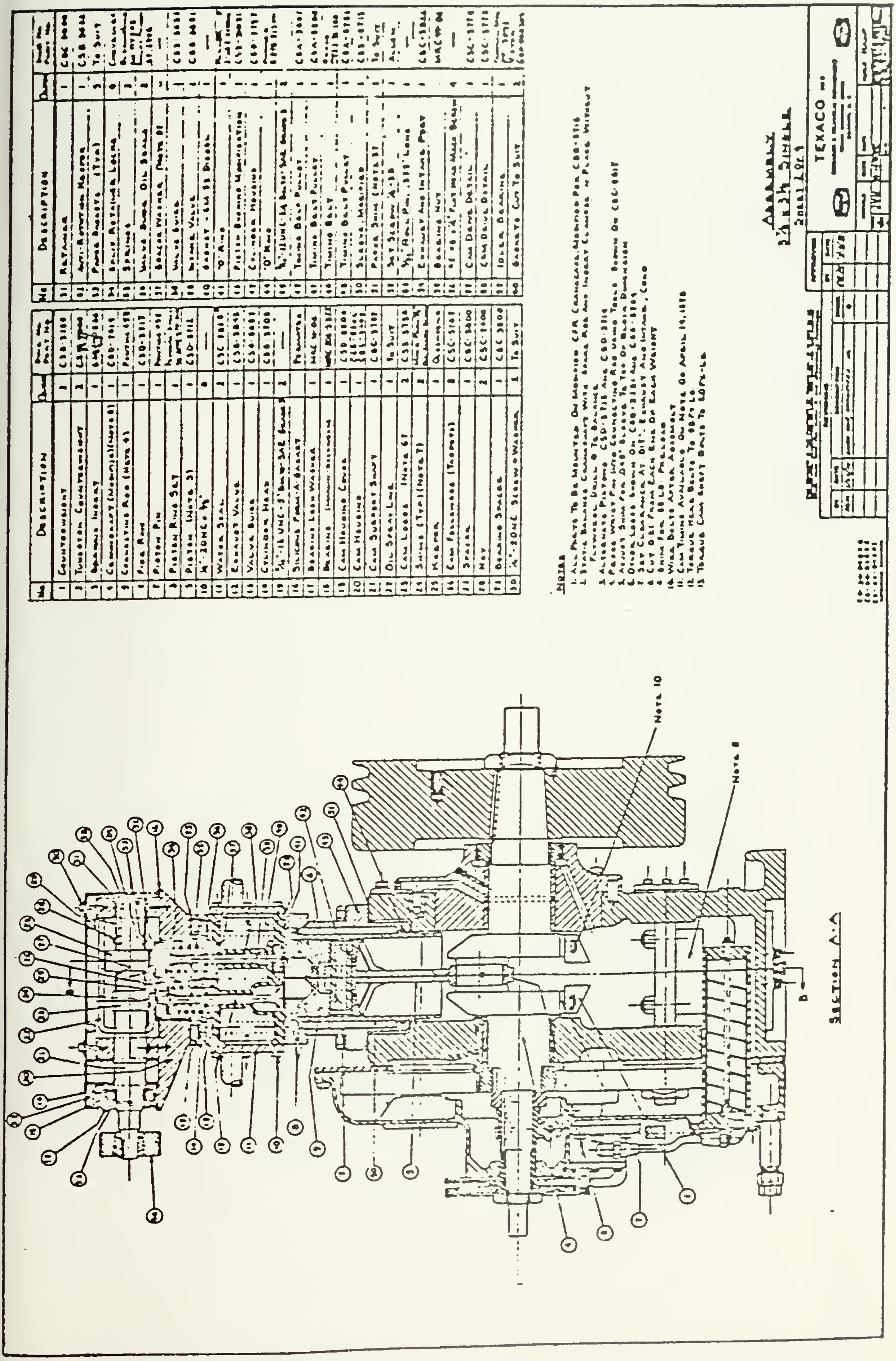


Fig.6a Single Cylinder Engine Assembly

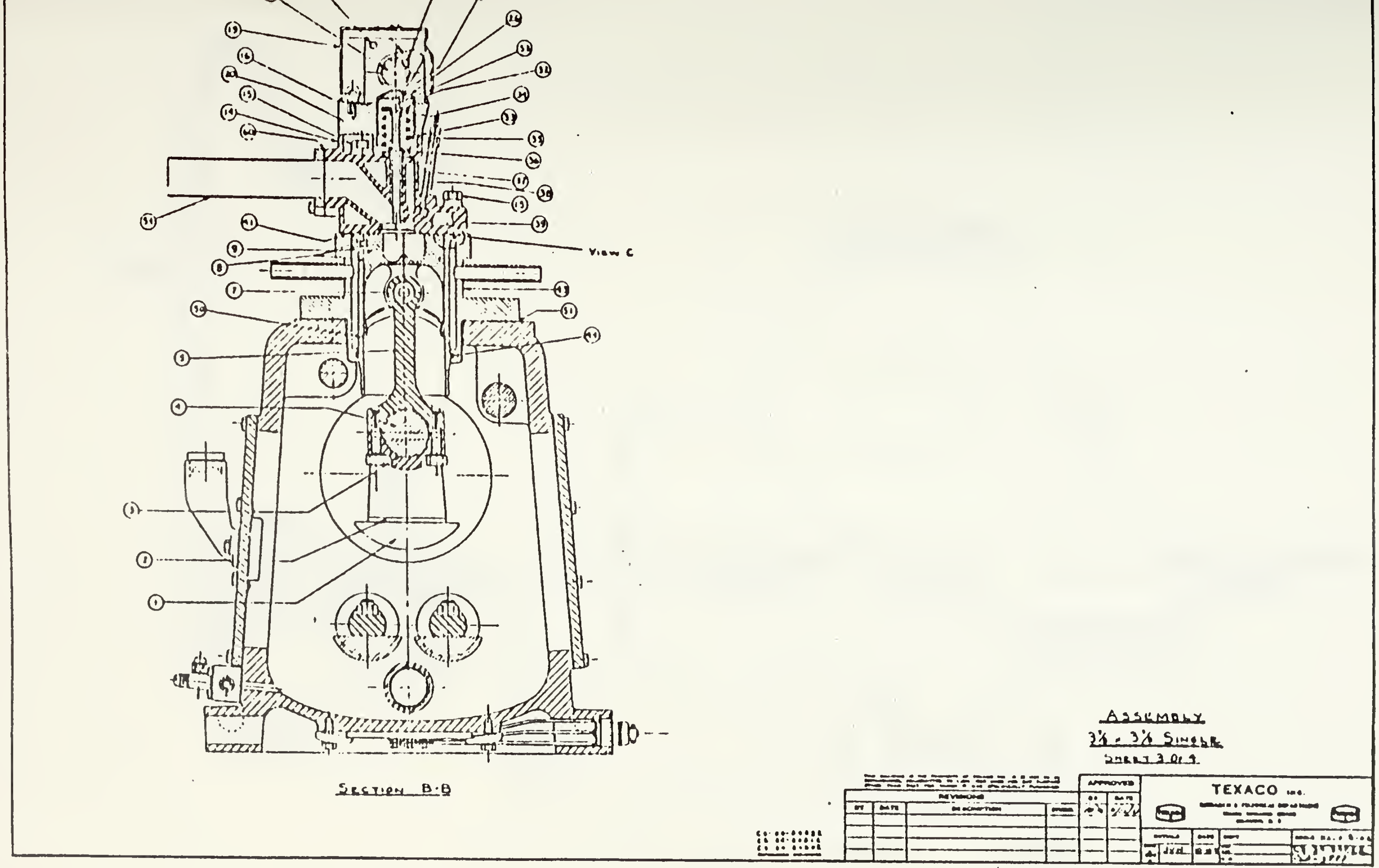


FIG. 6b SINGLE CYLINDER TEST ASSEMBLY

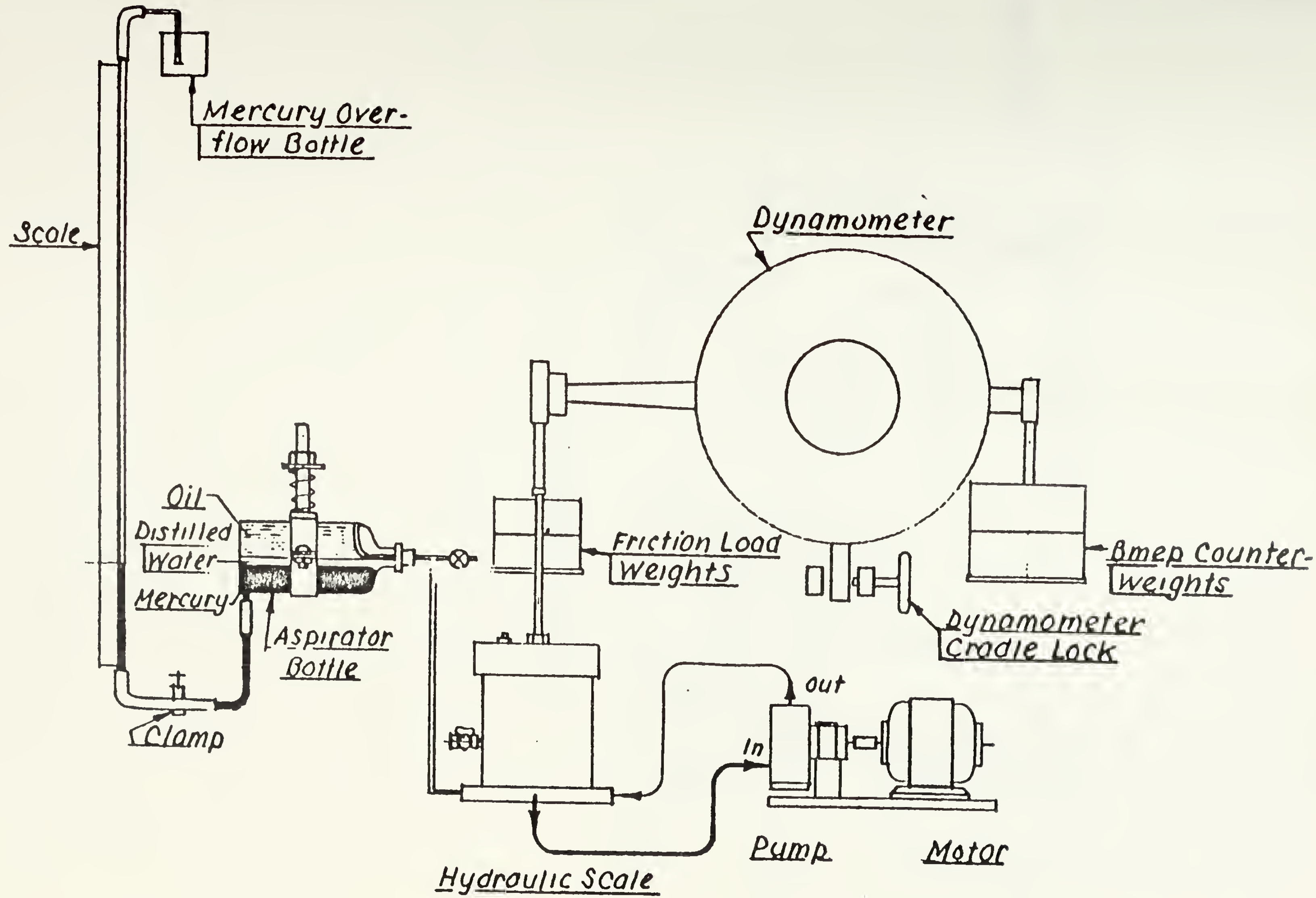


FIG. 7 DYNAMOMETER HYDRAULIC SCALE

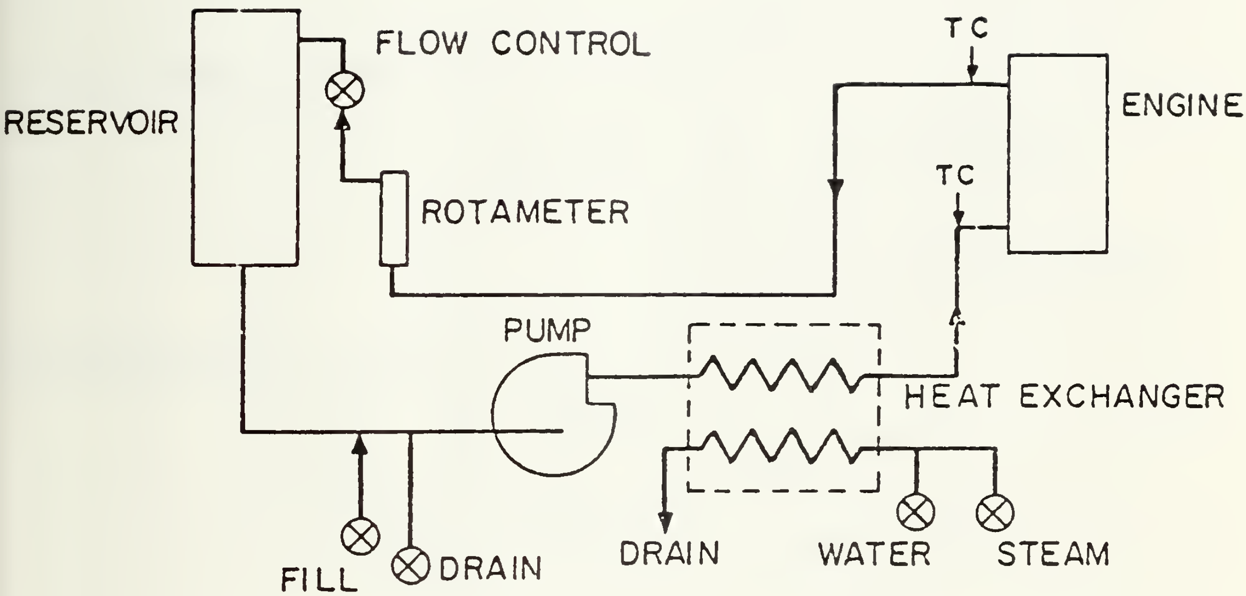


FIG. 8 COOLING SYSTEM

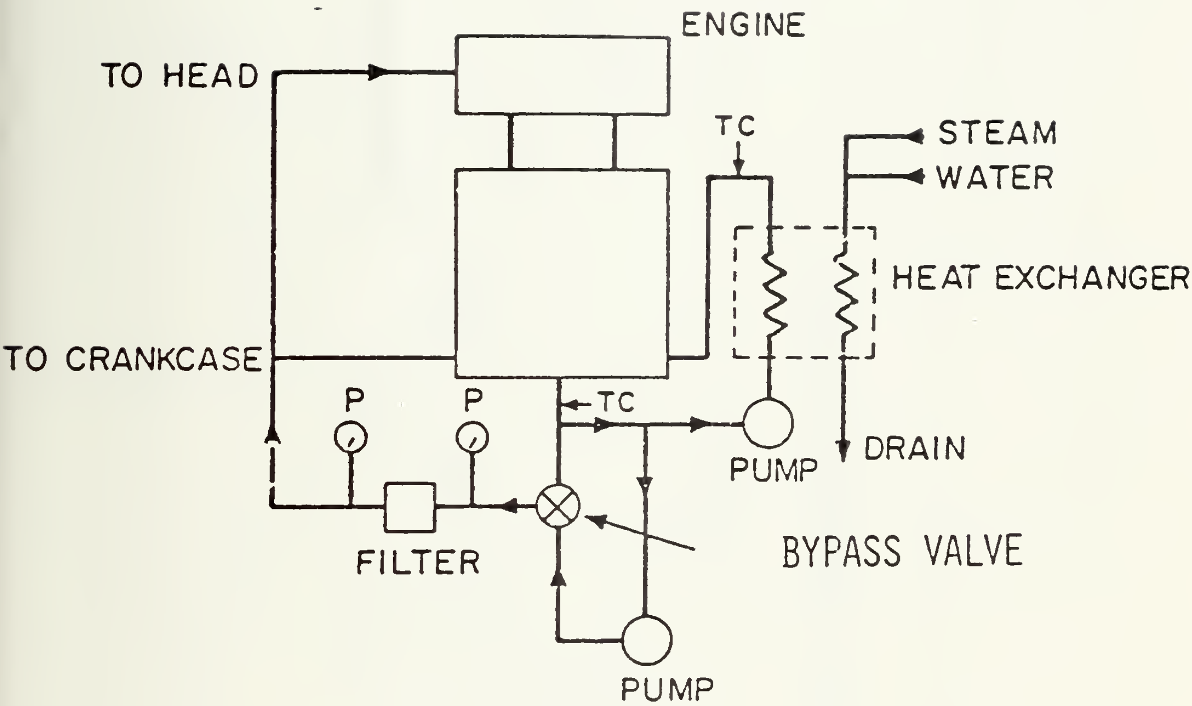


FIG. 9 LUBRICATION SYSTEM

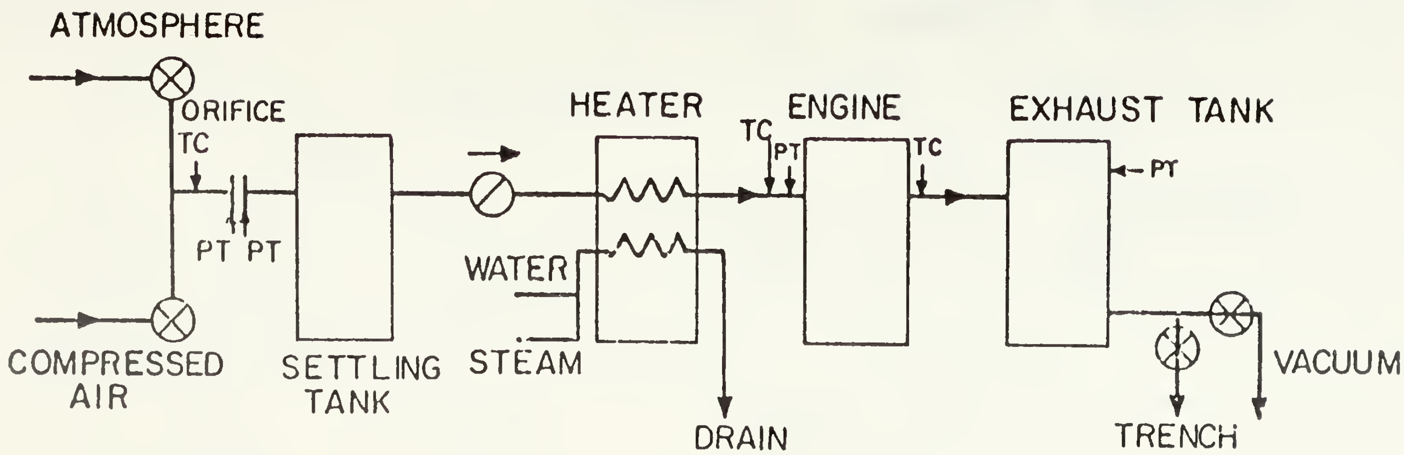


FIG. 10 INLET AND EXHAUST SYSTEM

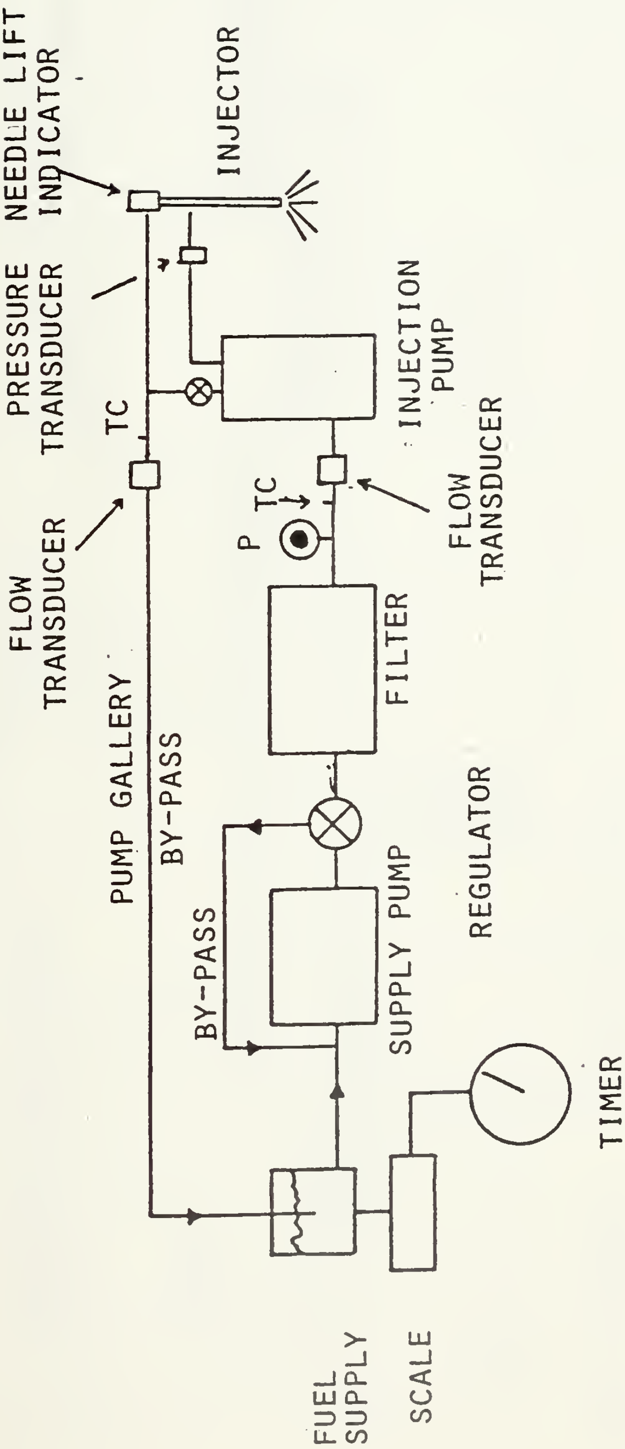


FIG. 11 FUEL SYSTEM

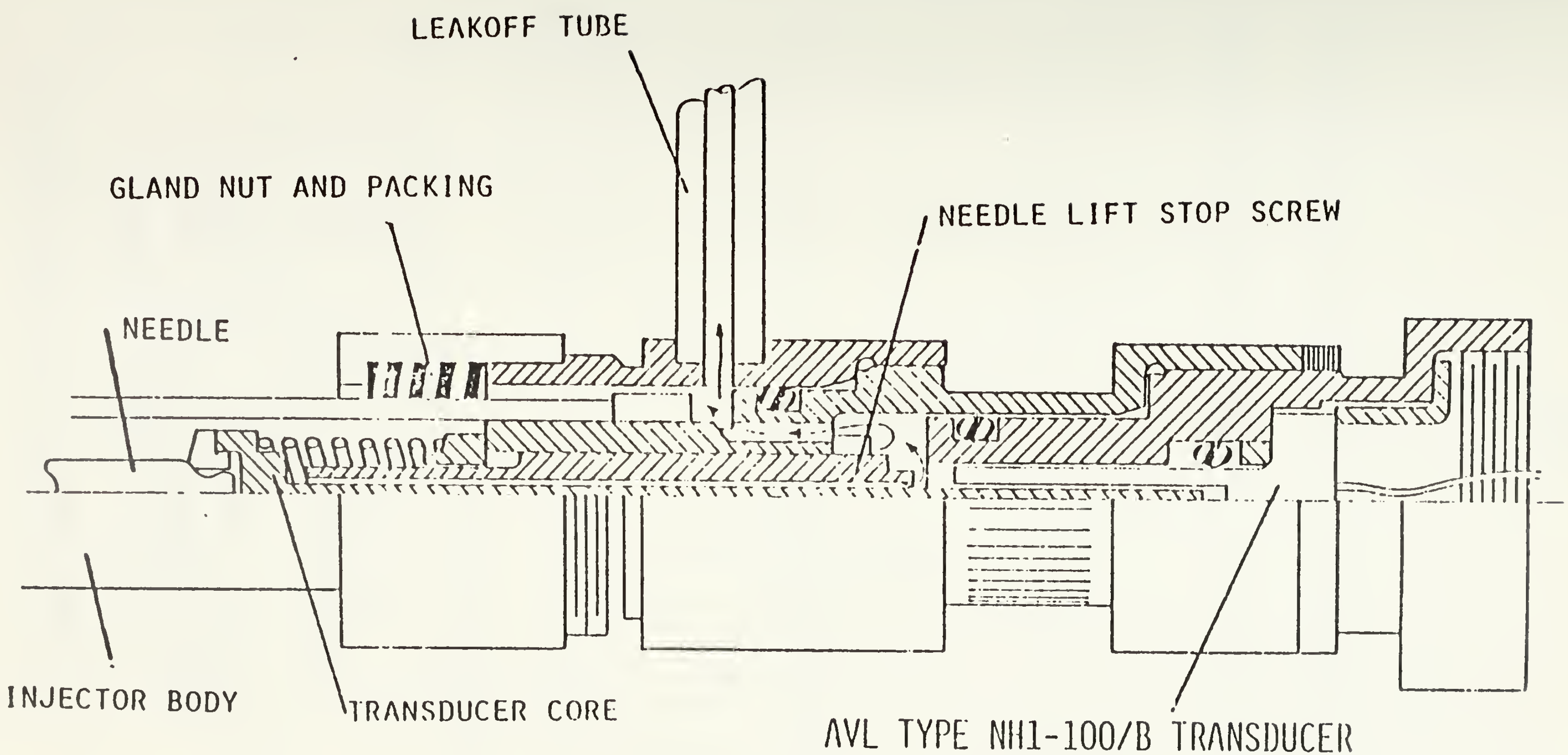
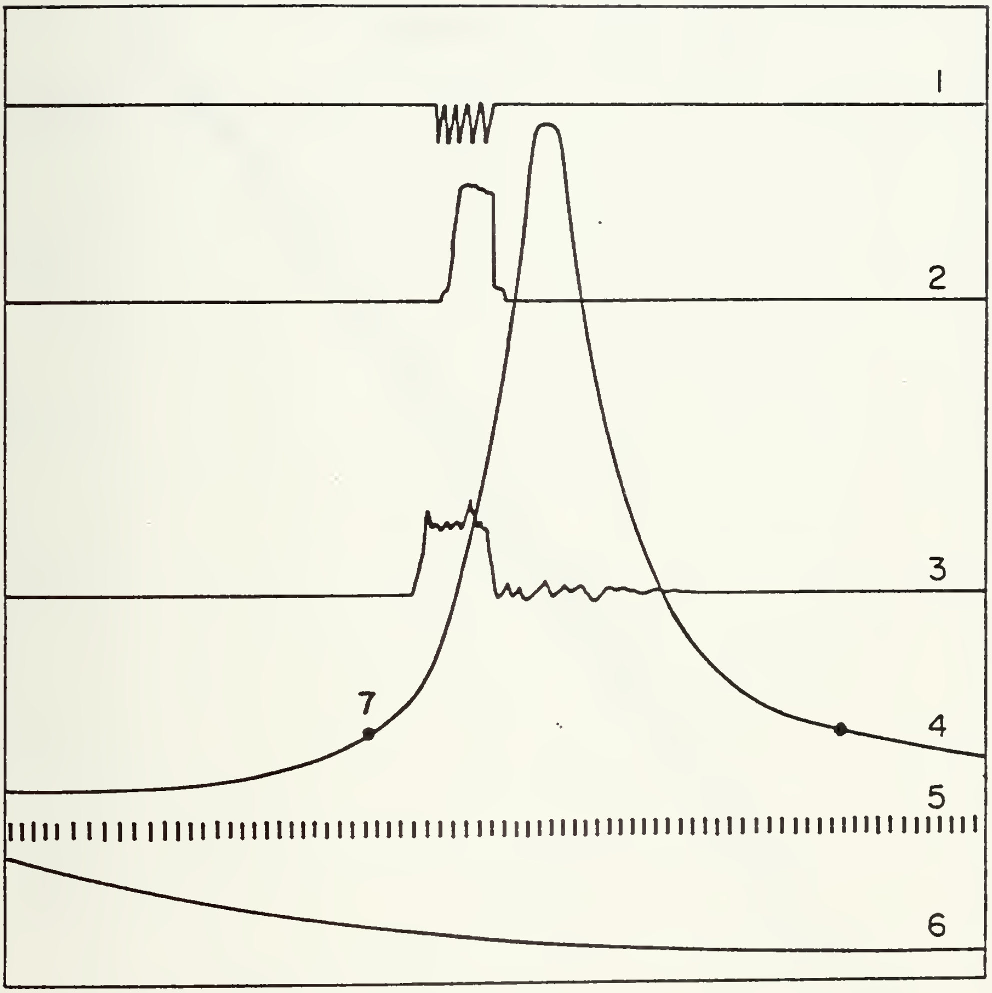


FIG. 12 INJECTOR LIFT TRANSDUCER ASSEMBLY



1. IGNITION DURATION
2. FUEL INJECTOR NEEDLE LIFT
3. FUEL INJECTION LINE PRESSURE
4. CYLINDER PRESSURE
5. CRANKANGLE INDICATOR, 1/5 CA^{O}
6. 185 CA^{O} BTDC REFERENCE SIGNAL
7. BALANCE PRESSURE INDICATOR

FIG.13-TYPICAL OSCILLOSCOPE TRACE

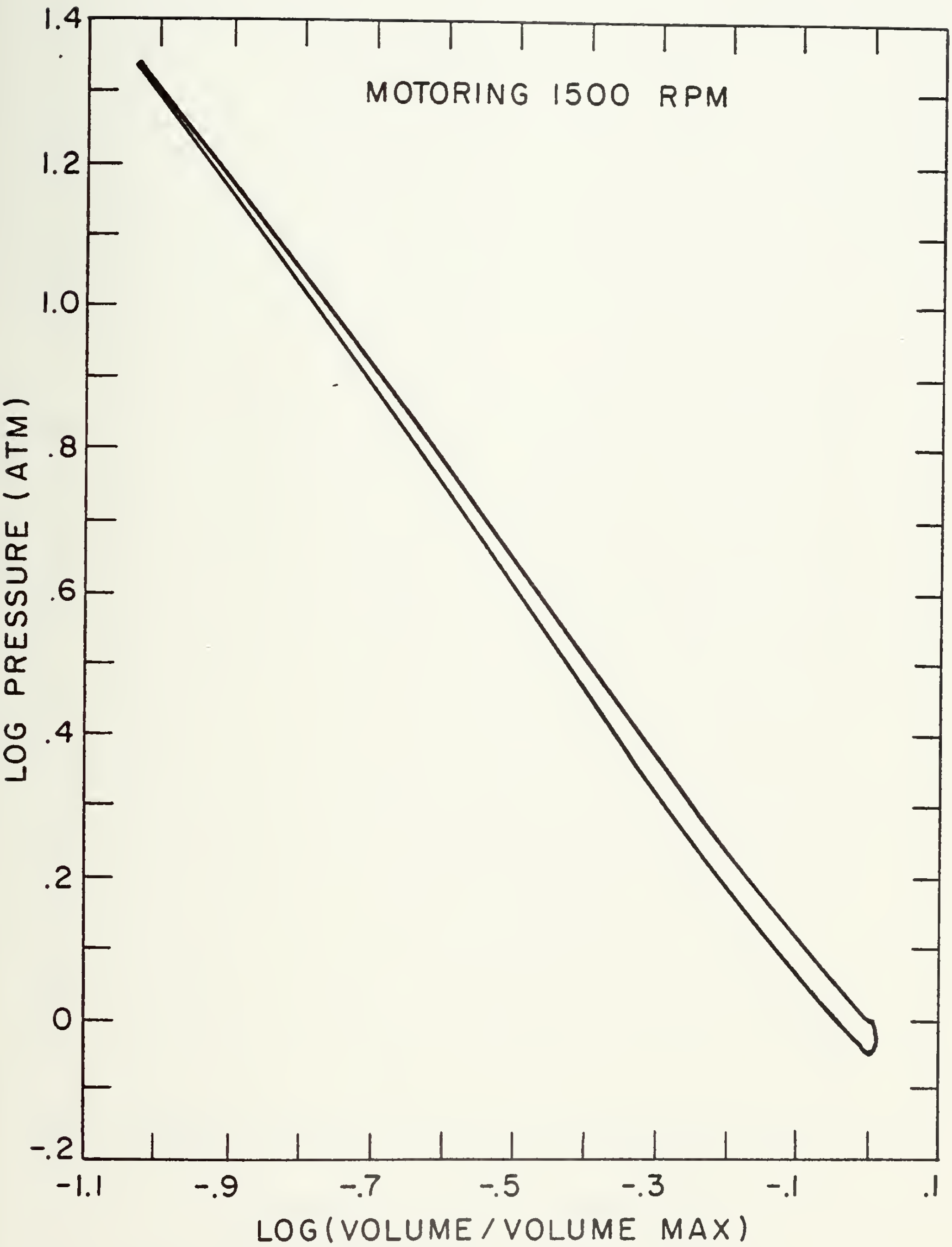


FIG. **14** 1500 RPM MOTORING LOG P VS LOG V

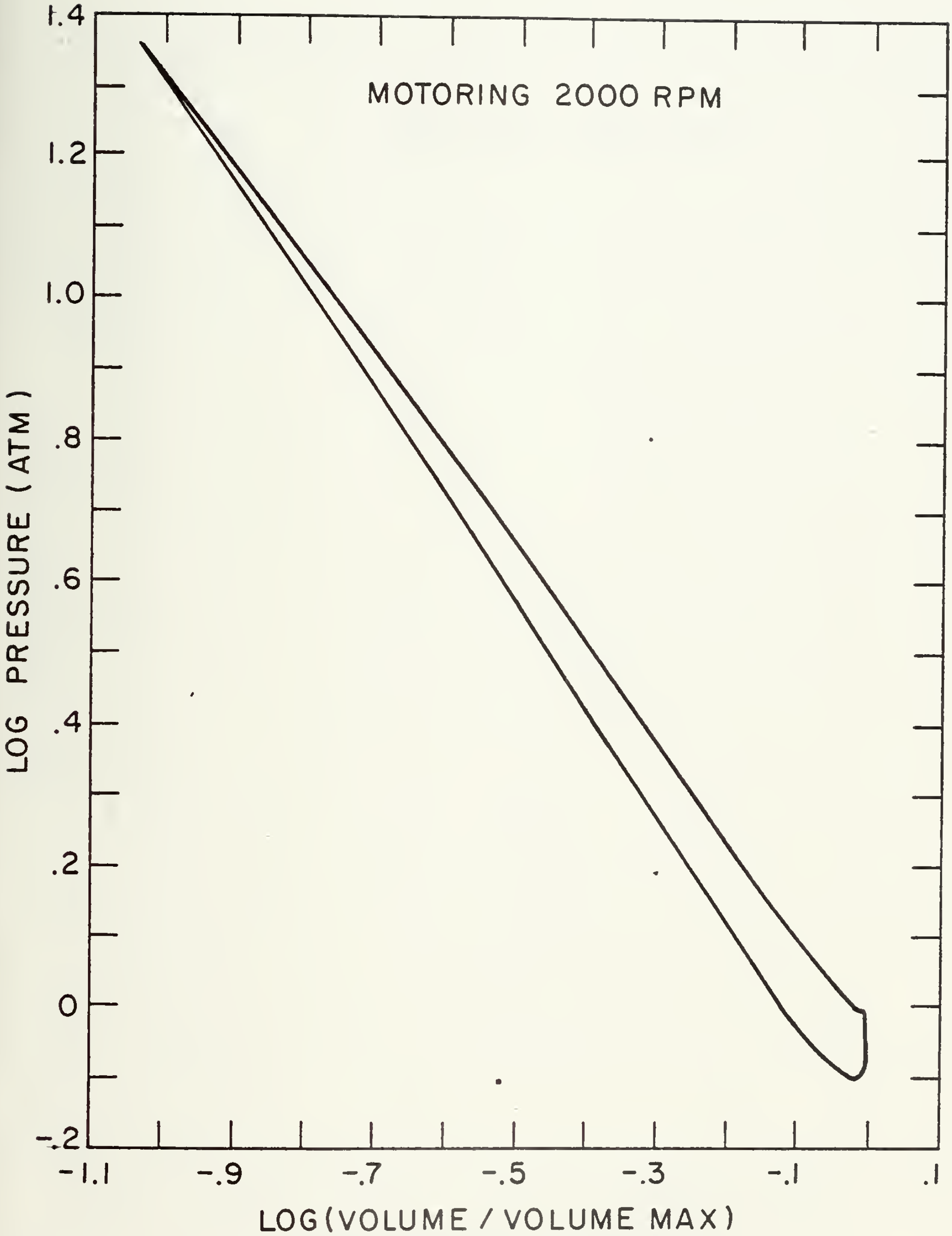


FIG. **15** 2000 RPM MOTORING LOG P VS LOG V

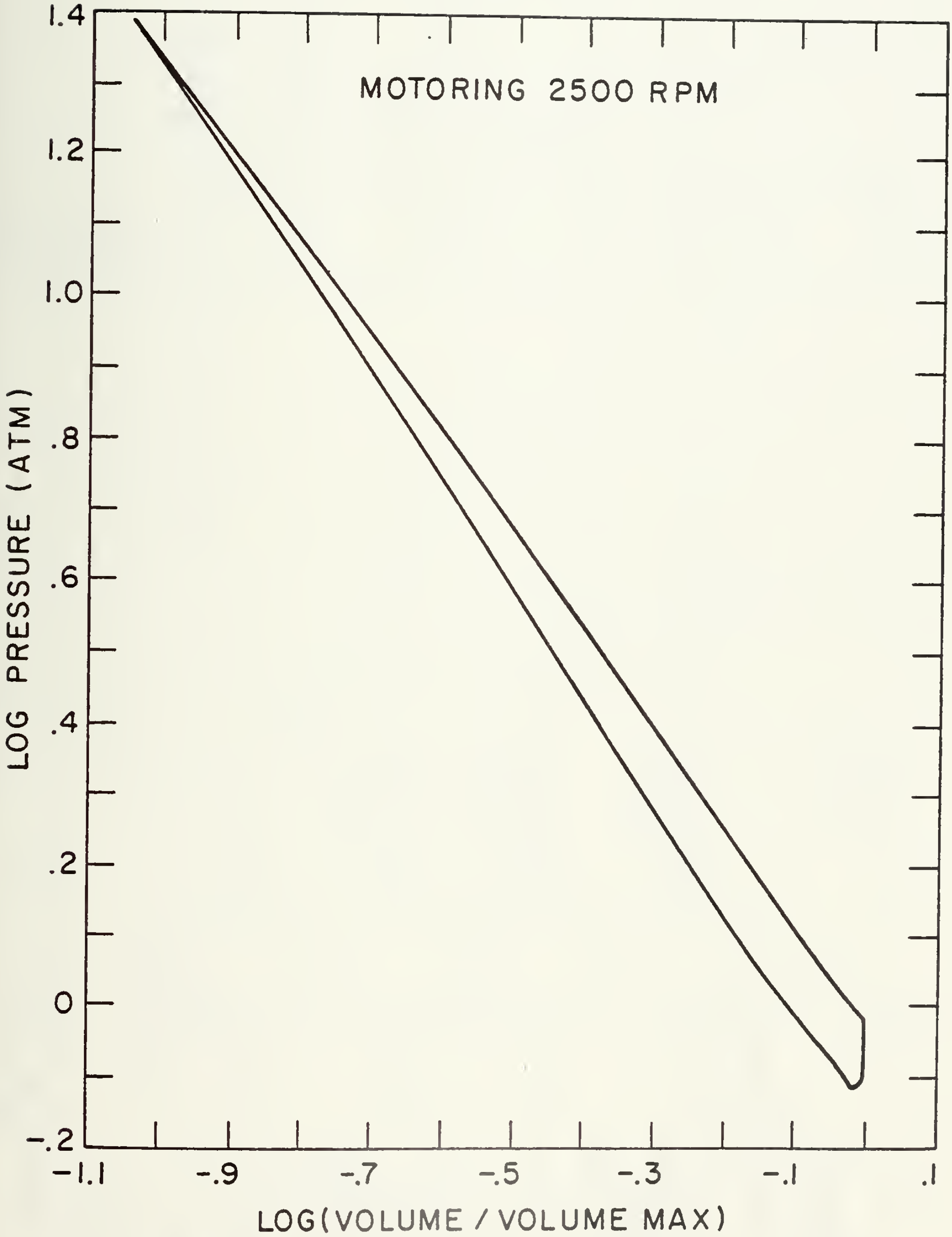


FIG. 16 2500 RPM MOTORING LOG P VS LOG V

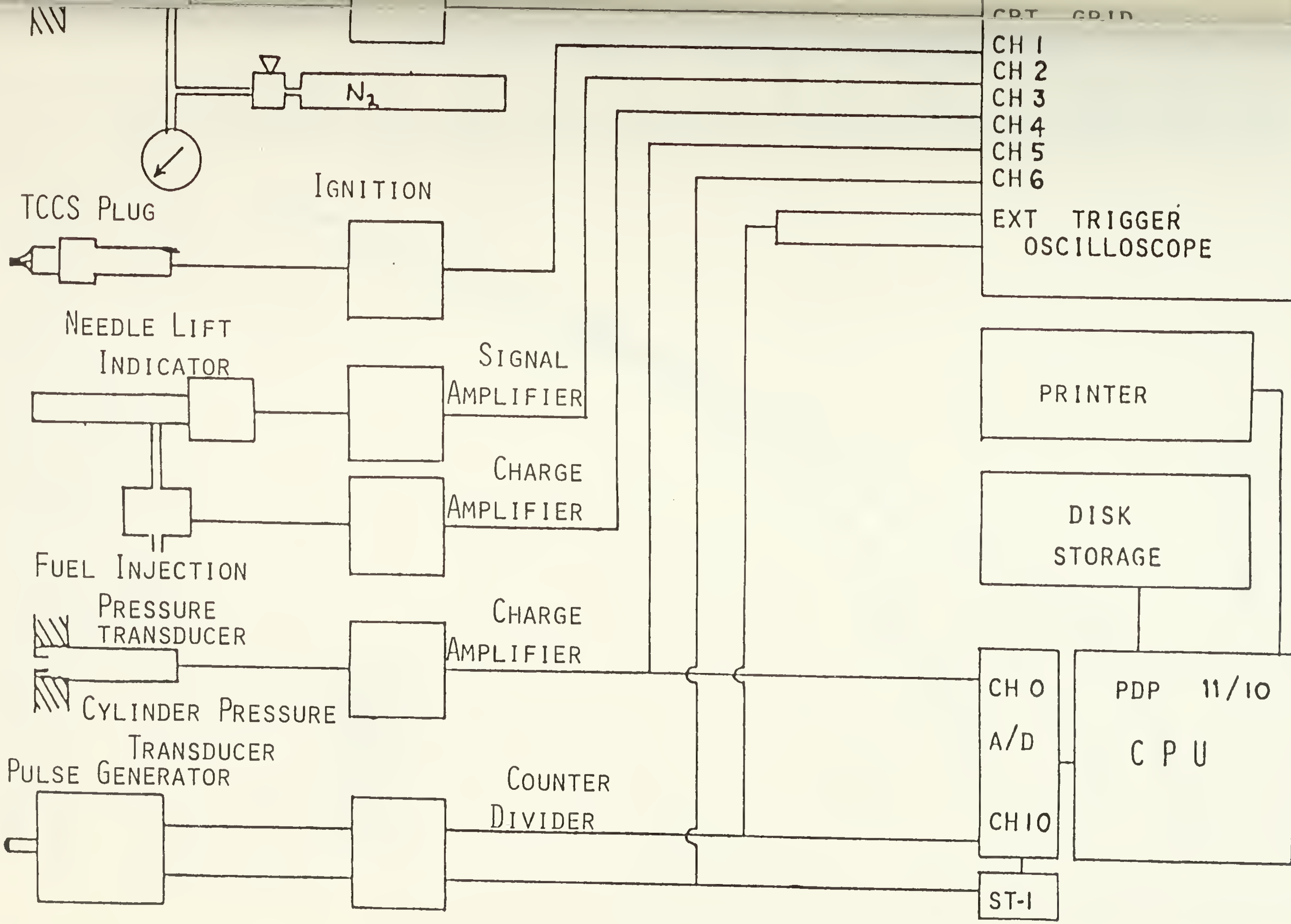


FIG. 17 SCHEMATIC OF DATA ACQUISITION SYSTEM

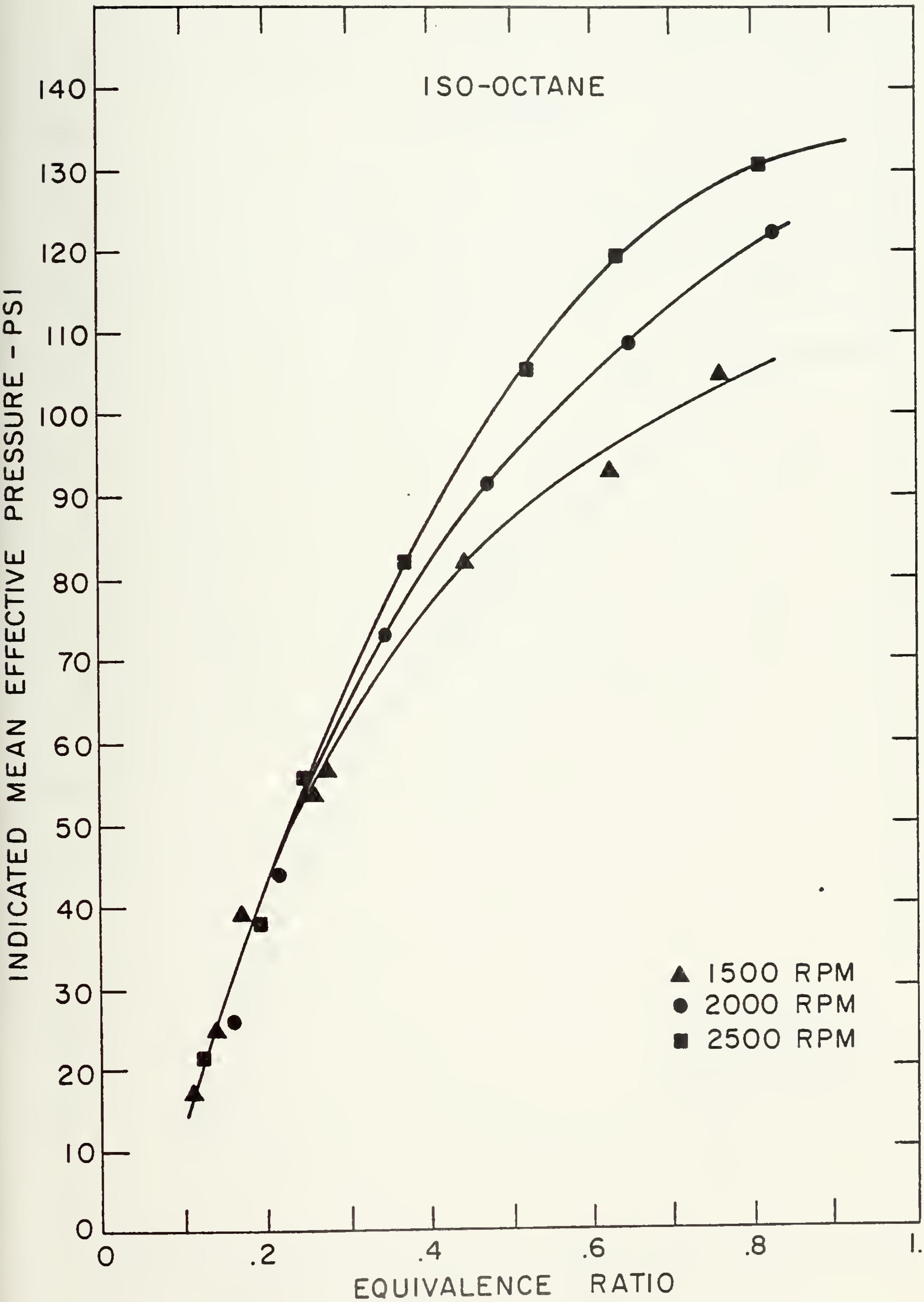


FIG. 18 INDICATED MEAN EFFECTIVE PRESSURE VS EQUIVALENCE RATIO, FOR ISO-OCTANE

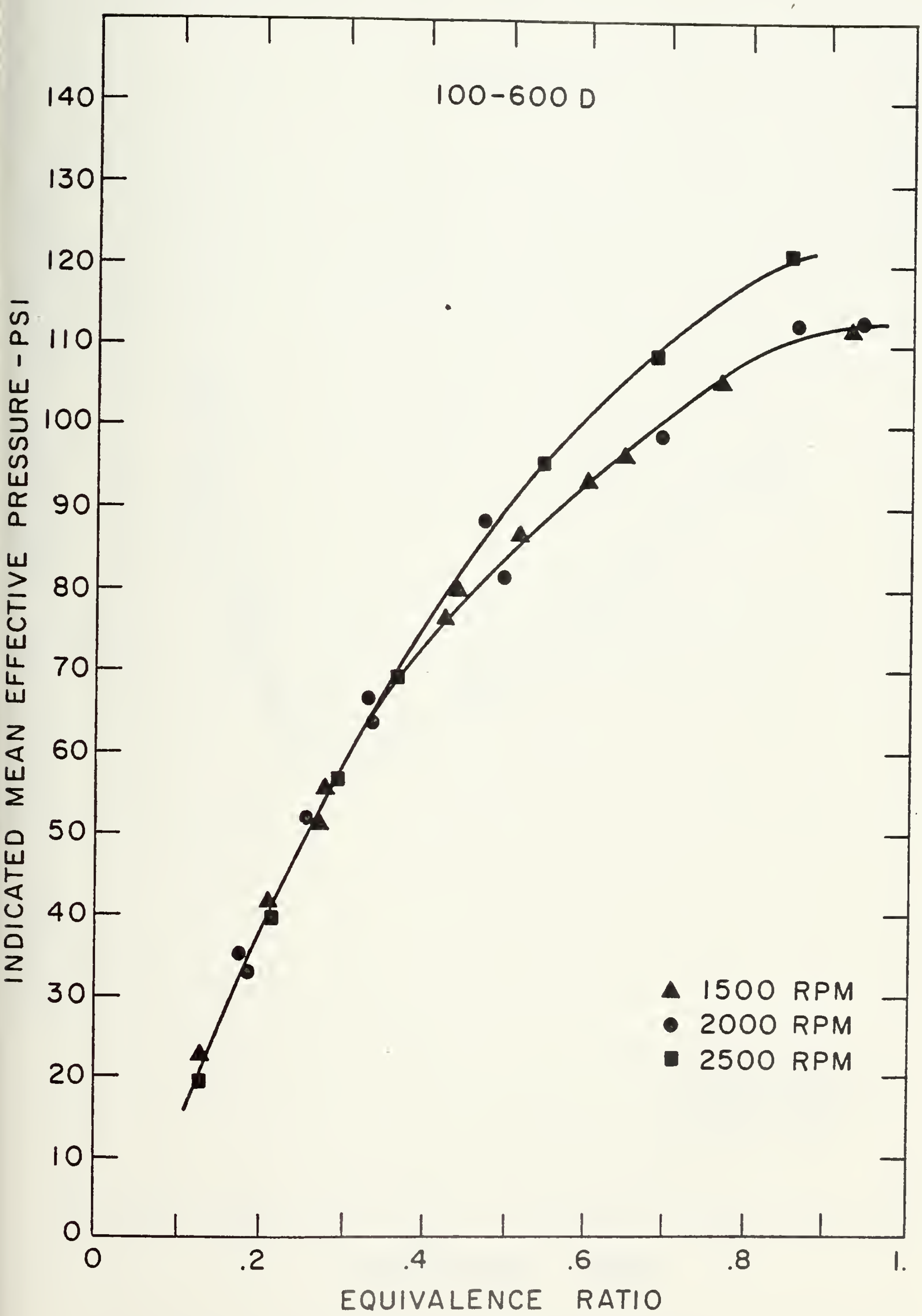


FIG. 19 INDICATED MEAN EFFECTIVE PRESSURE VS EQUIVALENCE RATIO, FOR 100-600 FUEL

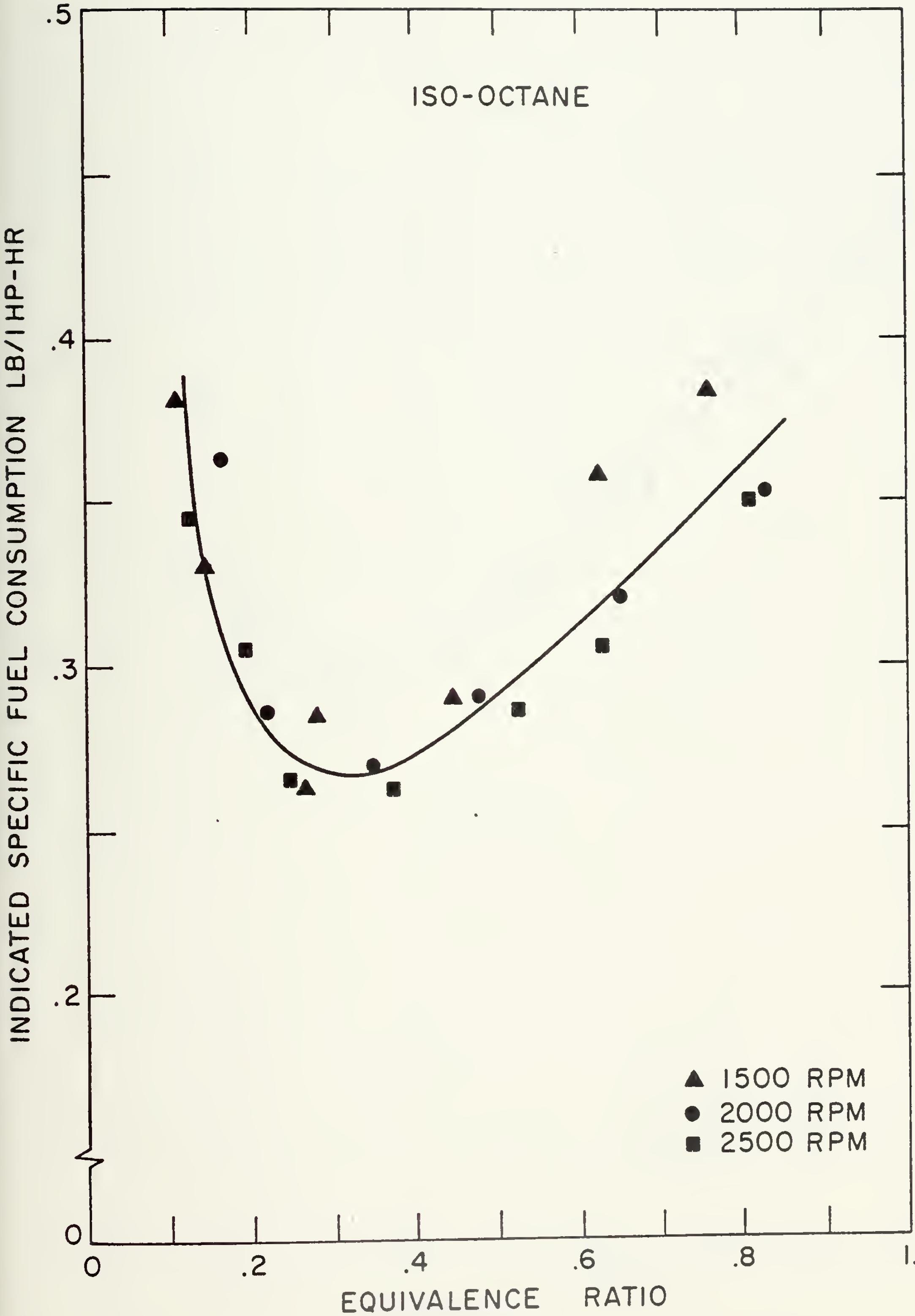


FIG. **20** INDICATED SPECIFIC FUEL CONSUMPTION VS EQUIVALENCE RATIO, FOR ISO-OCTANE

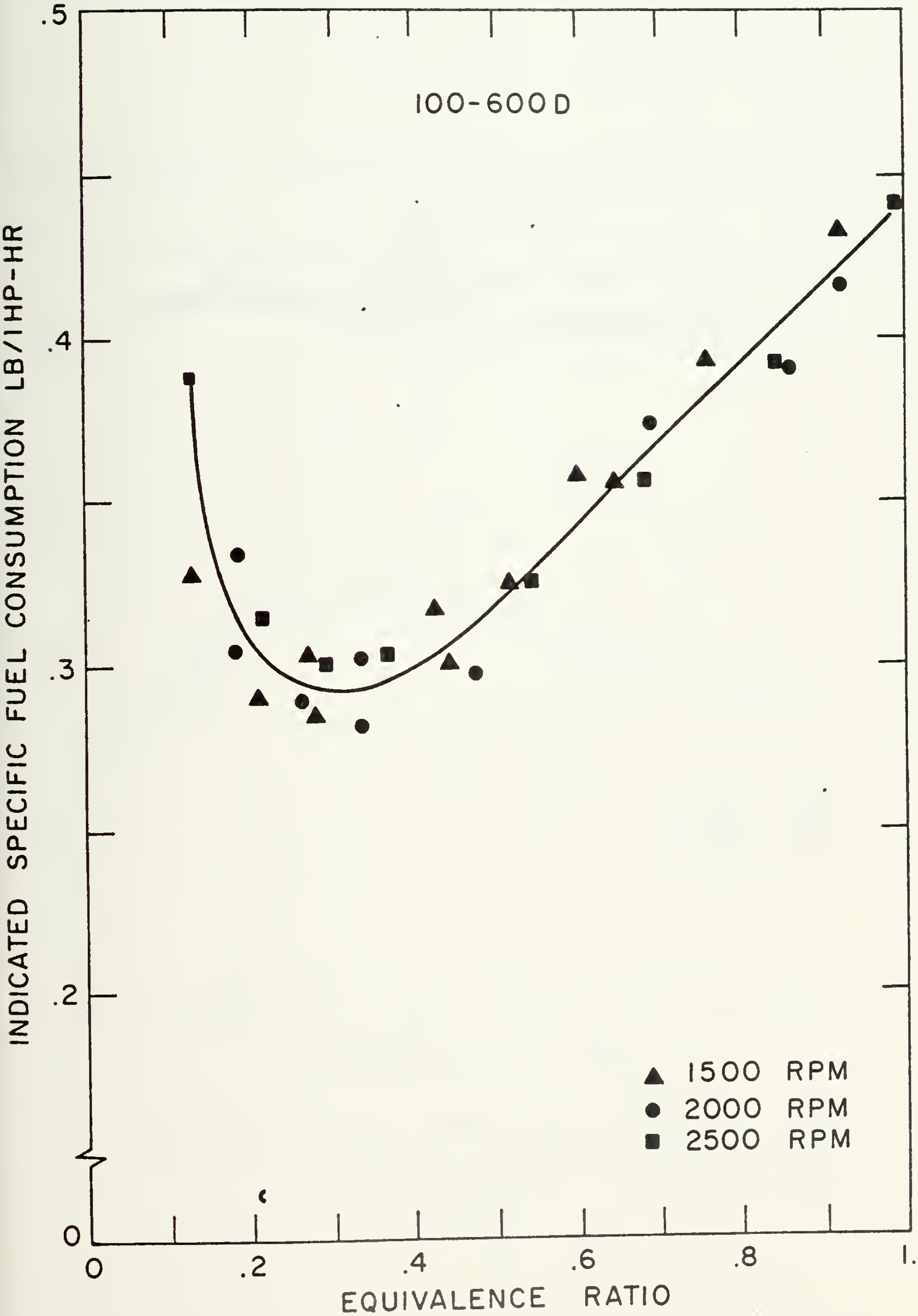


FIG. **21** INDICATED SPECIFIC FUEL CONSUMPTION VS EQUIVALENCE RATIO, FOR 100-600 FUEL

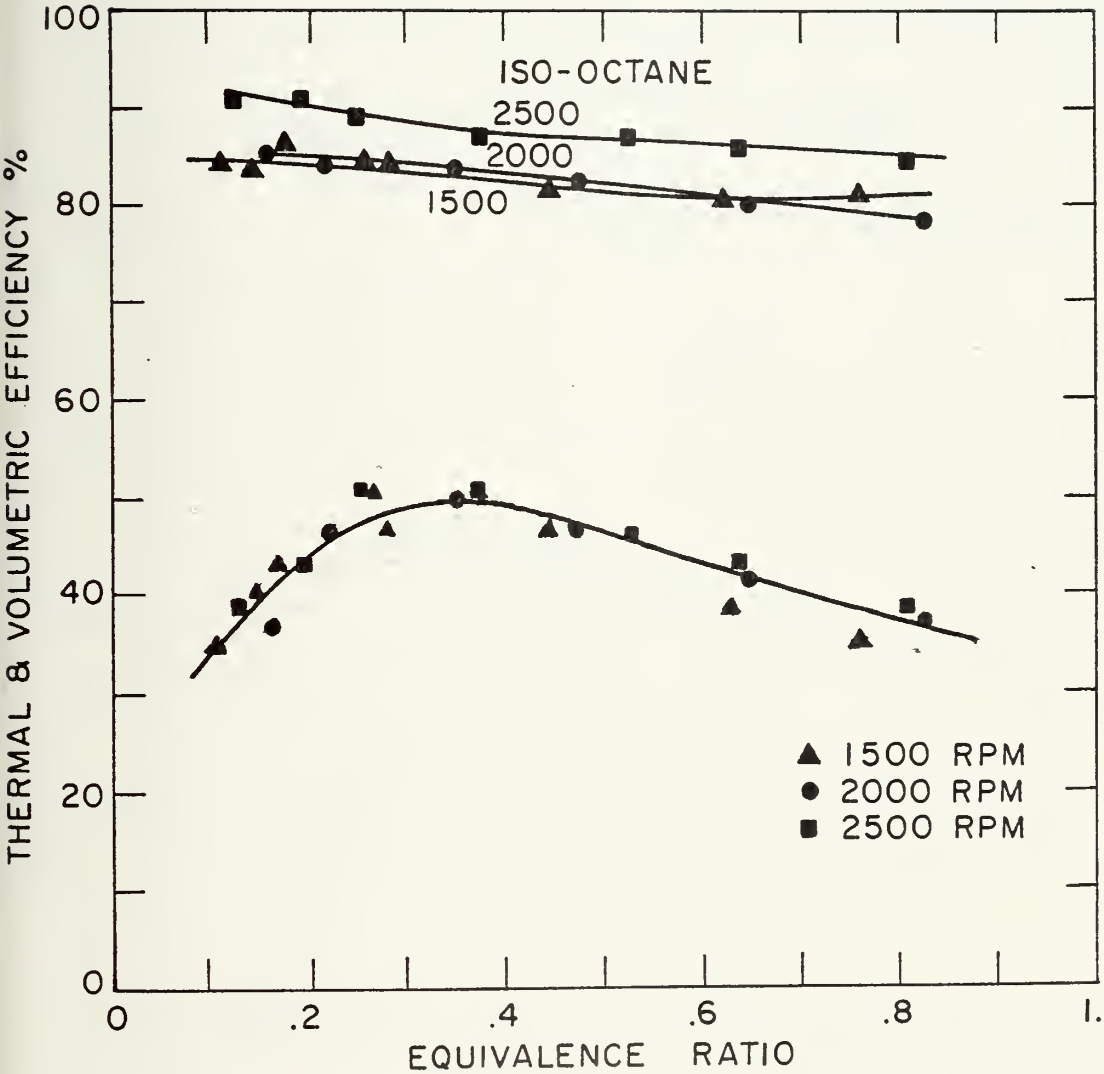


FIG. **22** INDICATED THERMAL AND VOLEMETRIC EFFICIENCY VS EQUIVALENCE RATIO FOR ISO-OCTANE

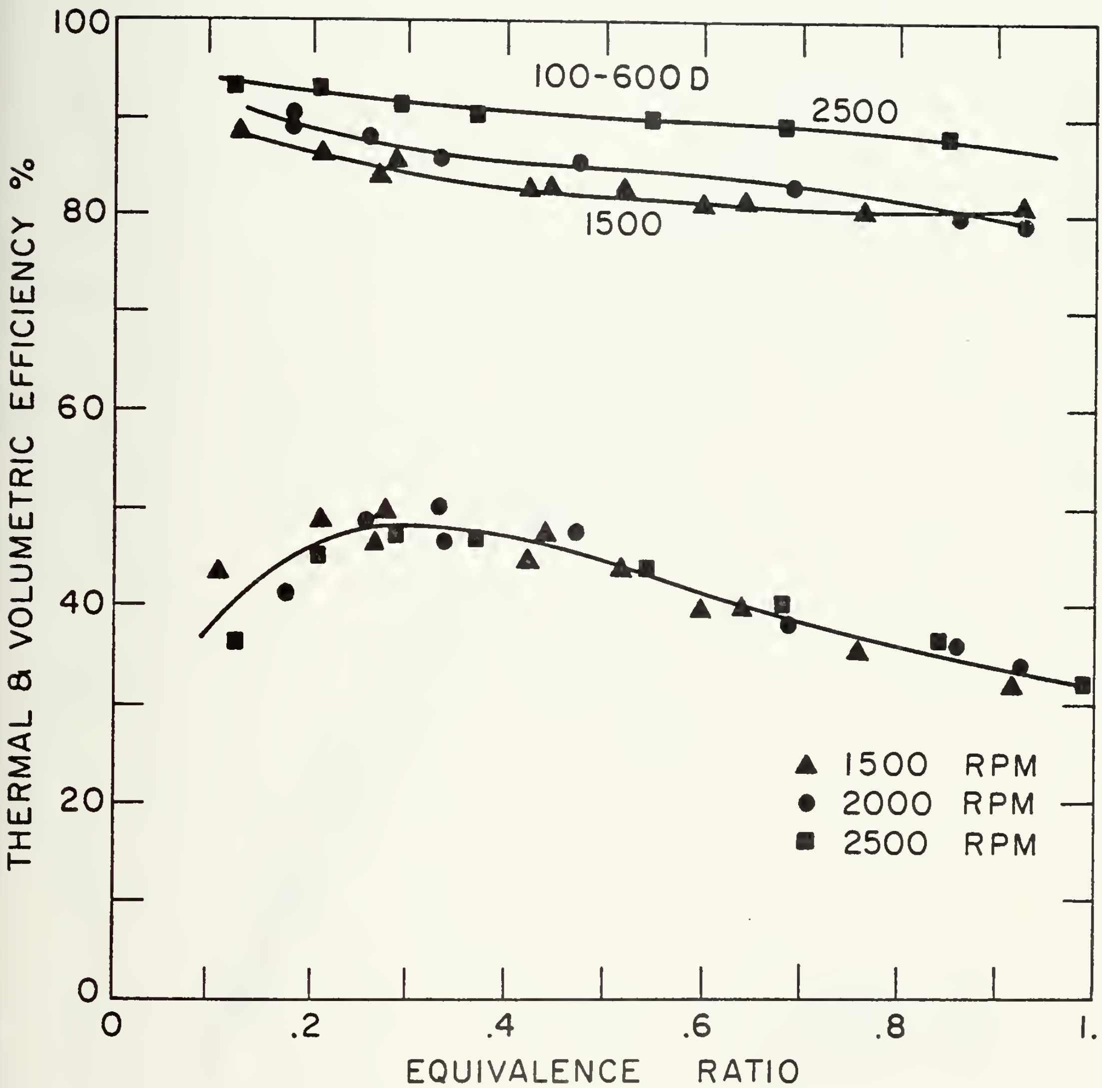


FIG. **23** INDICATED THERMAL AND VOLUMETRIC EFFICIENCY VS EQUIVALENCE RATIO FOR 100-600 FUEL

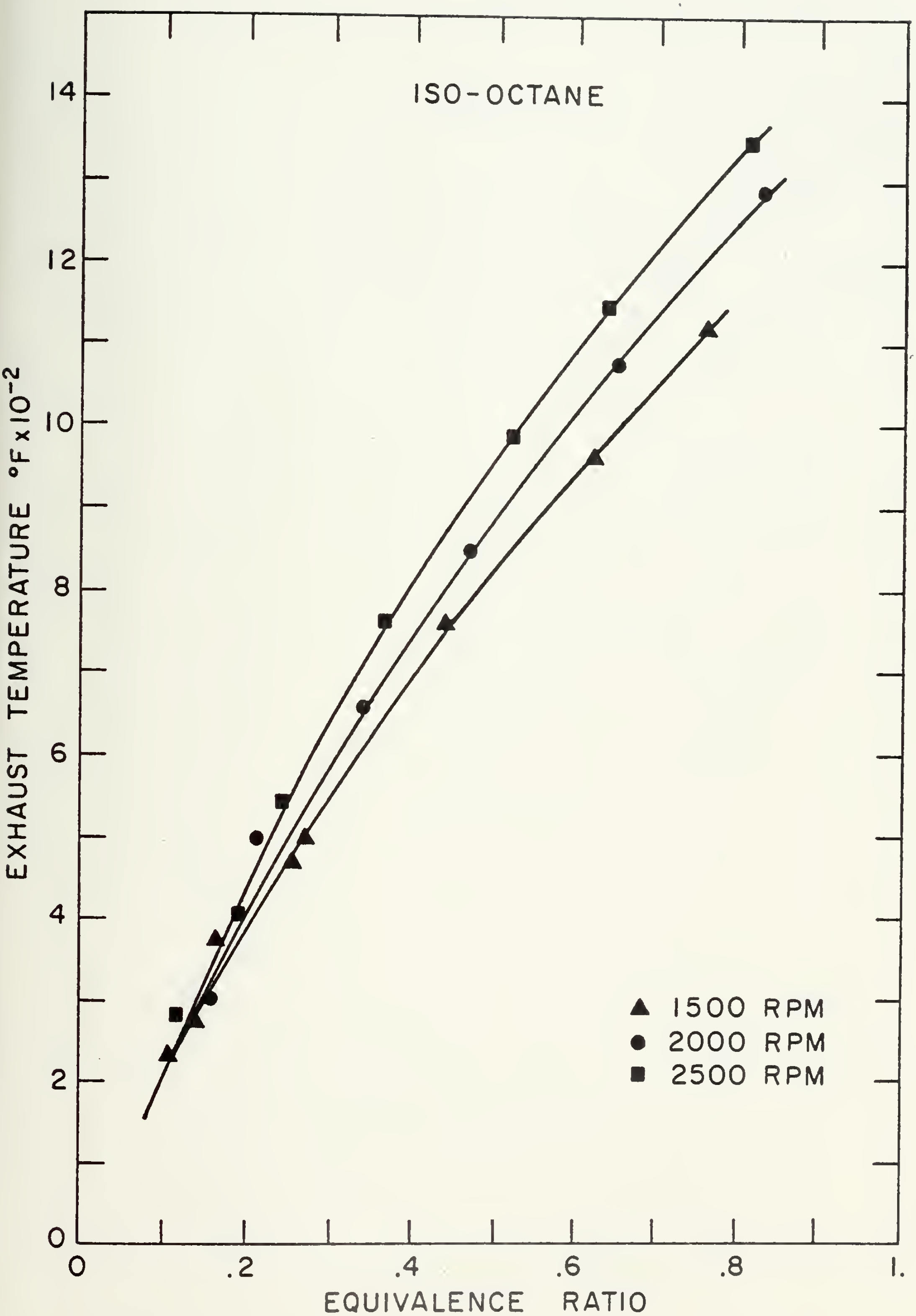


FIG. **24** EXHAUST TEMPERATURE VS EQUIVALENCE RATIO FOR ISO-OCTANE

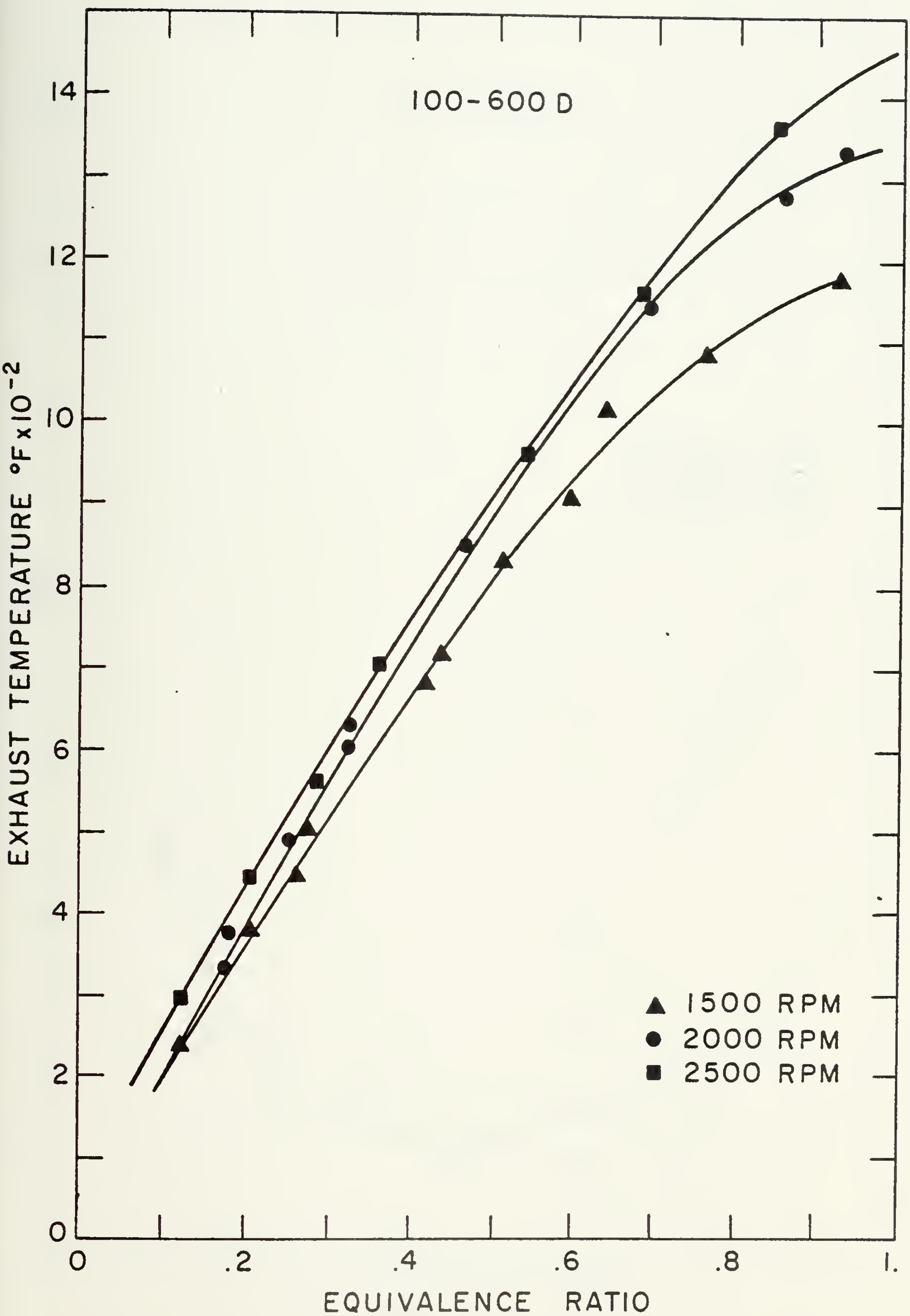


FIG. **25** EXHAUST TEMPERATURE VS EQUIVALENCE RATIO FOR 100-600 FUEL

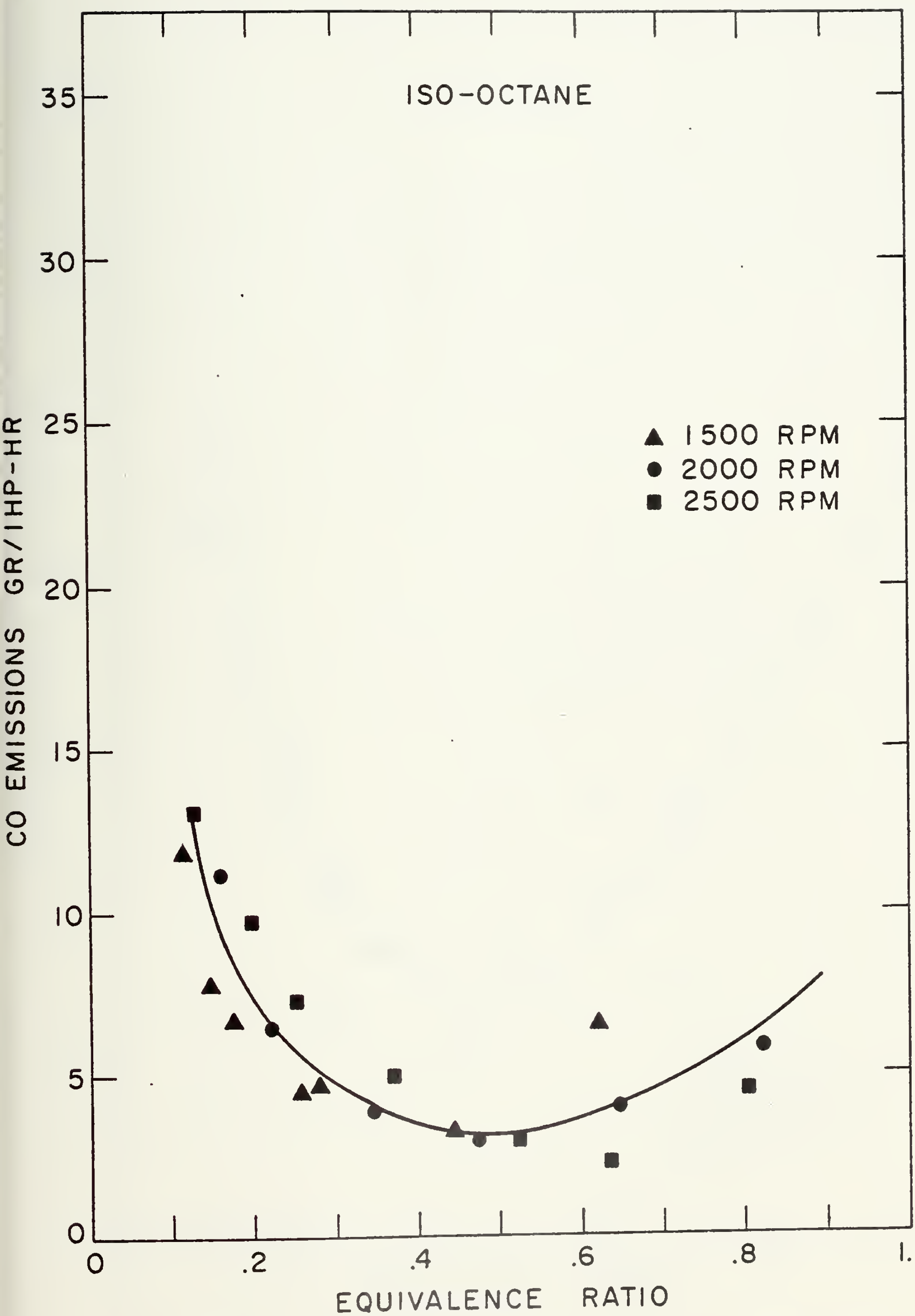


FIG. **26** CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

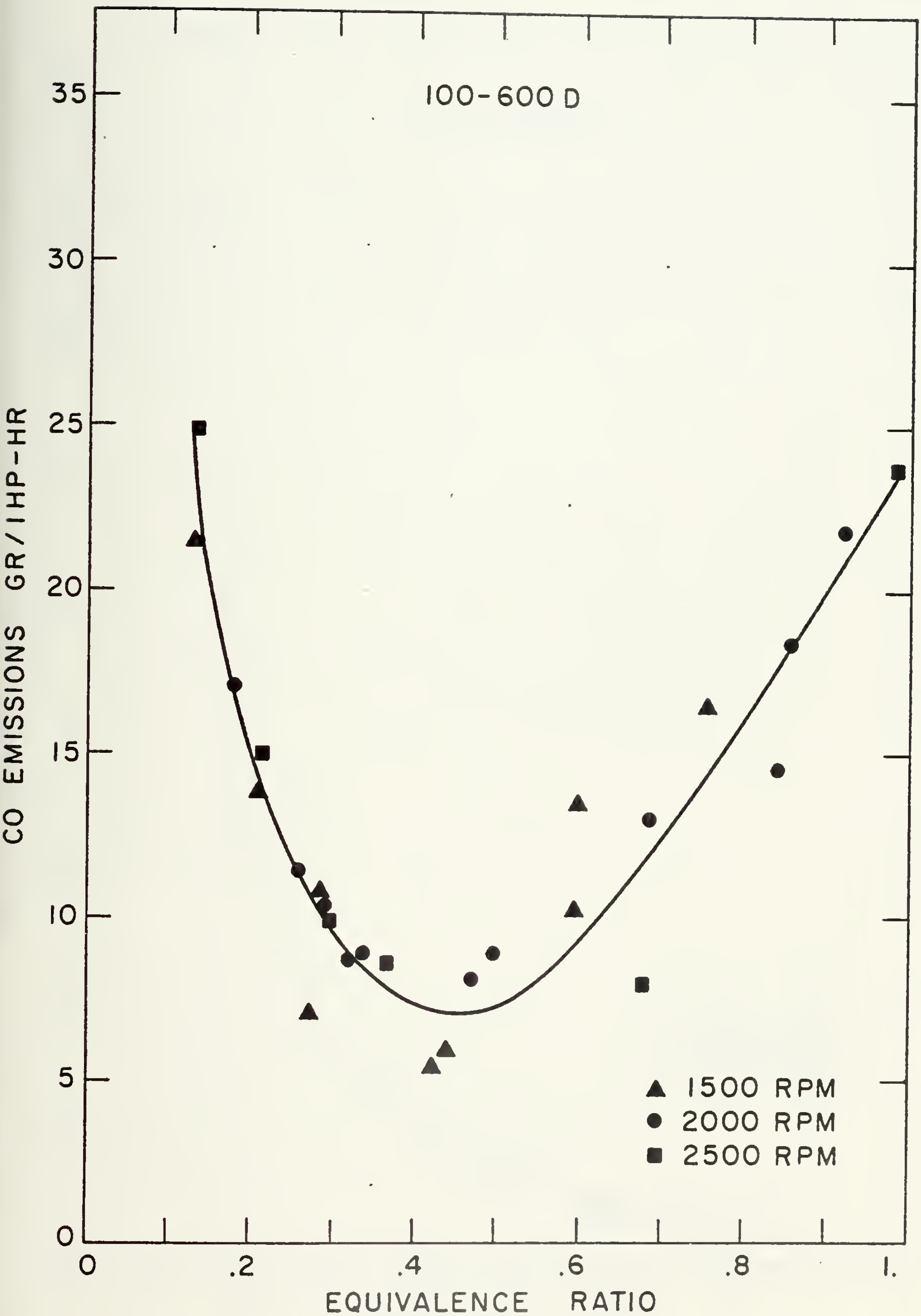


FIG. 27 CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

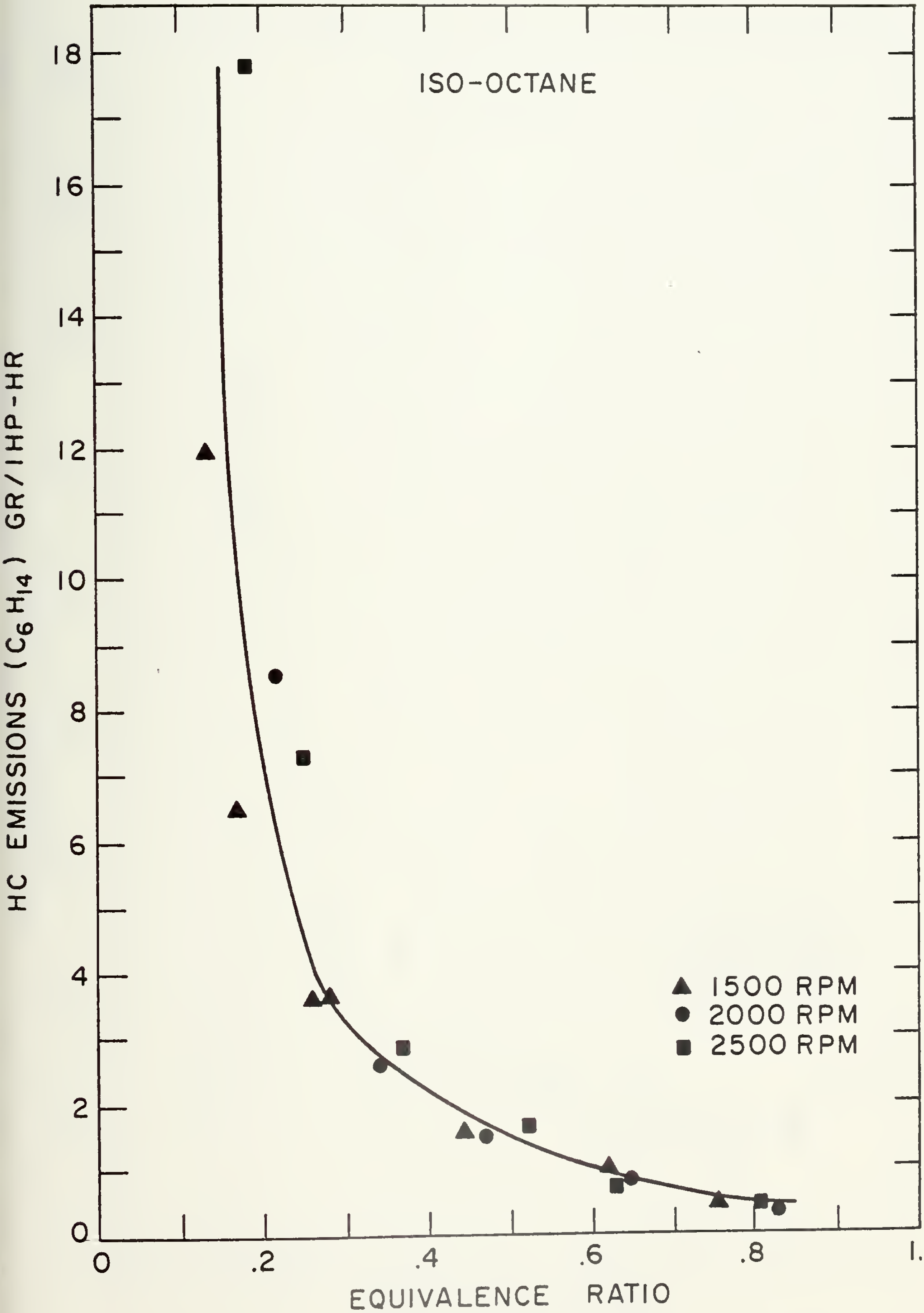


FIG. **28** HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

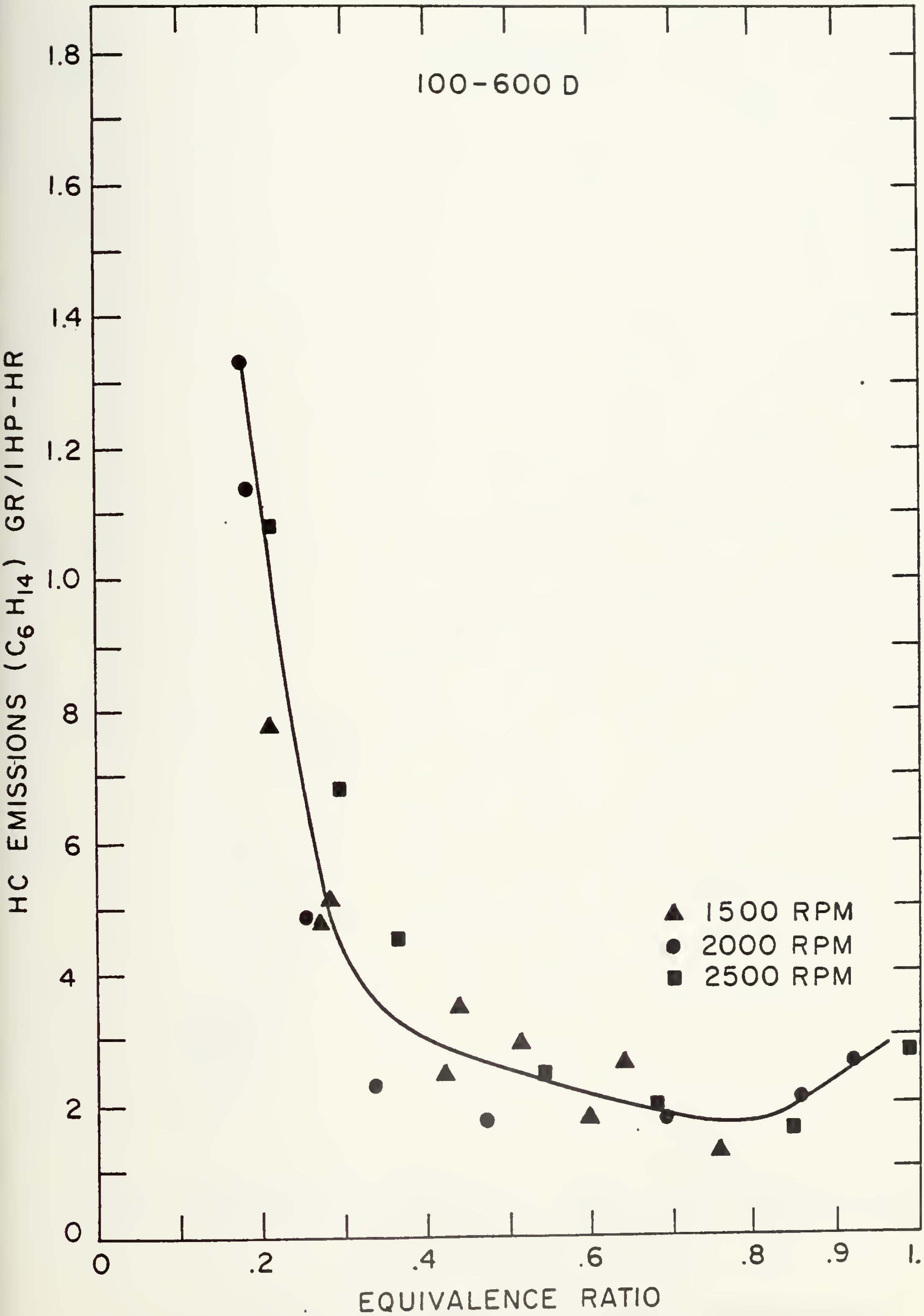


FIG. 29 HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

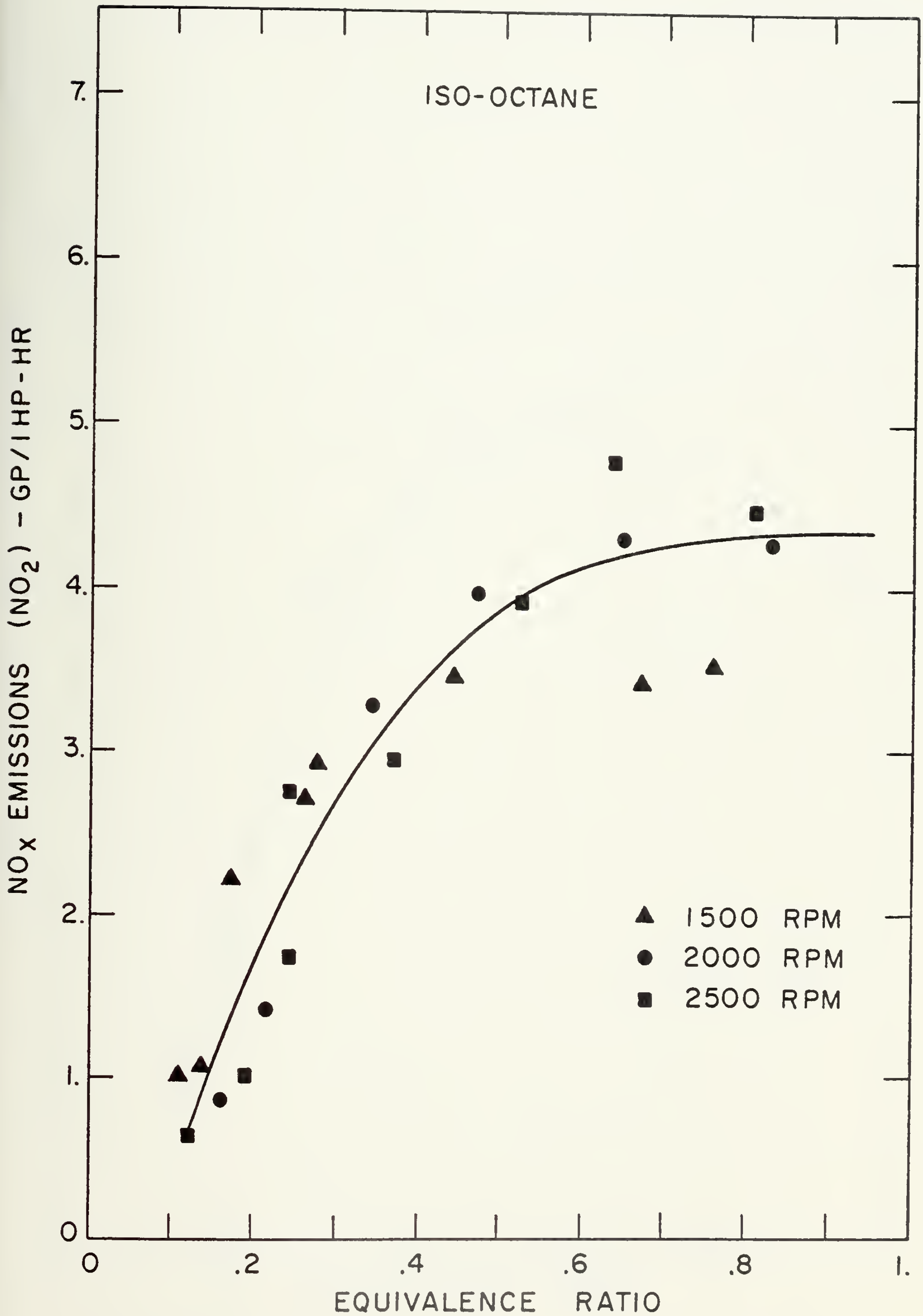


FIG. 30 NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

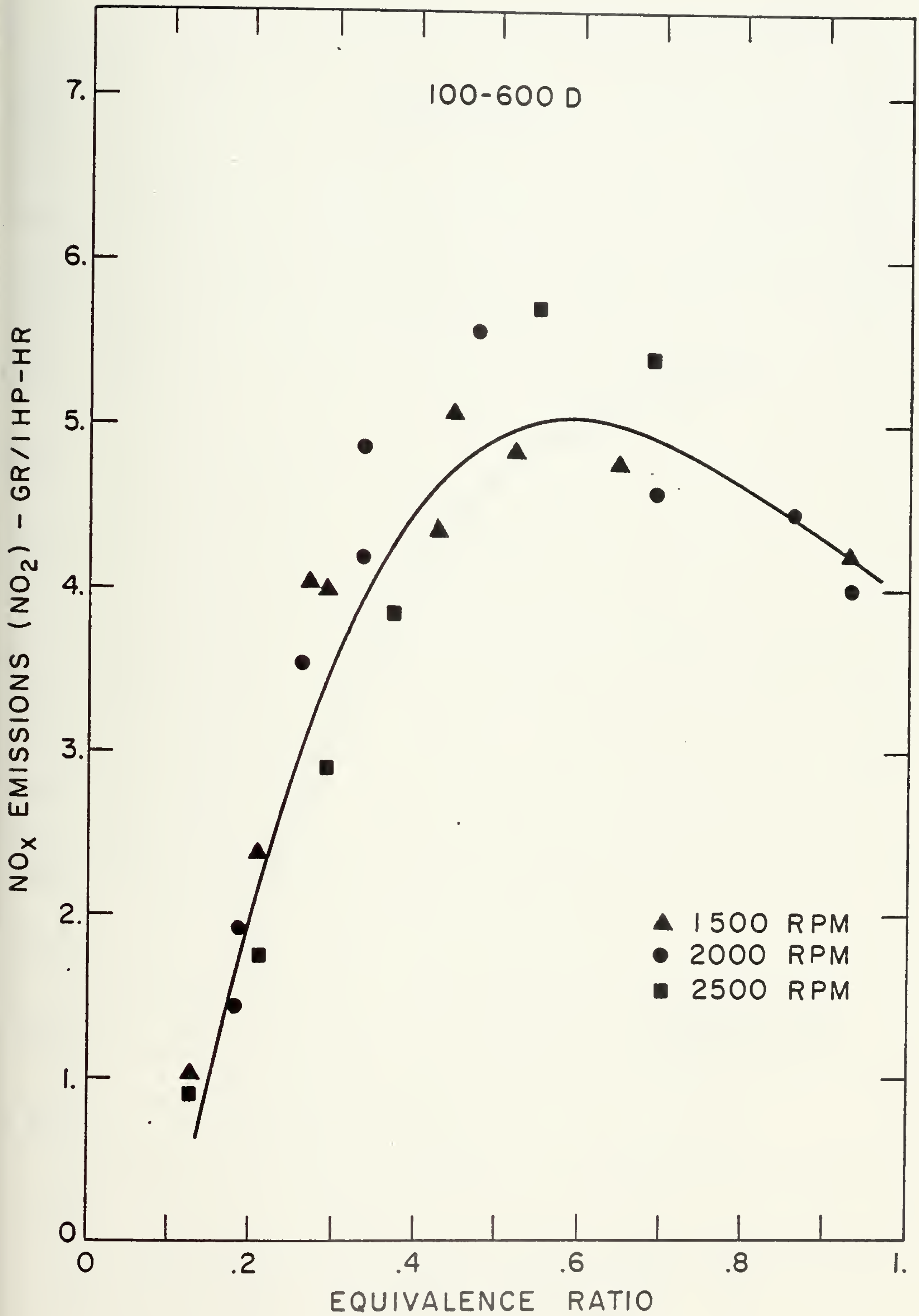


FIG. **31** NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

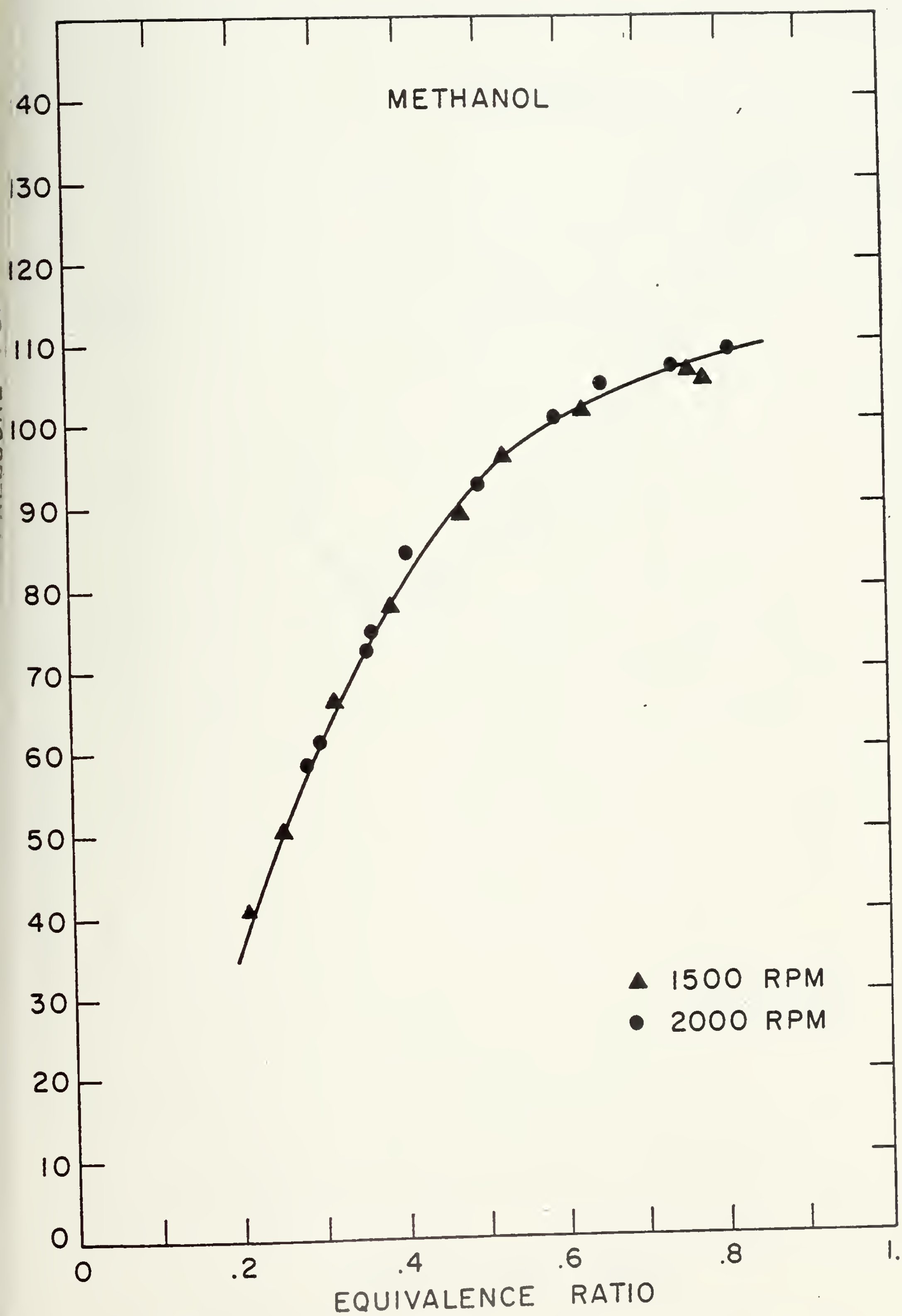


FIG. **32** INDICATED MEAN EFFECTIVE PRESSURE VS EQUIVALENCE RATIO FOR METHANOL

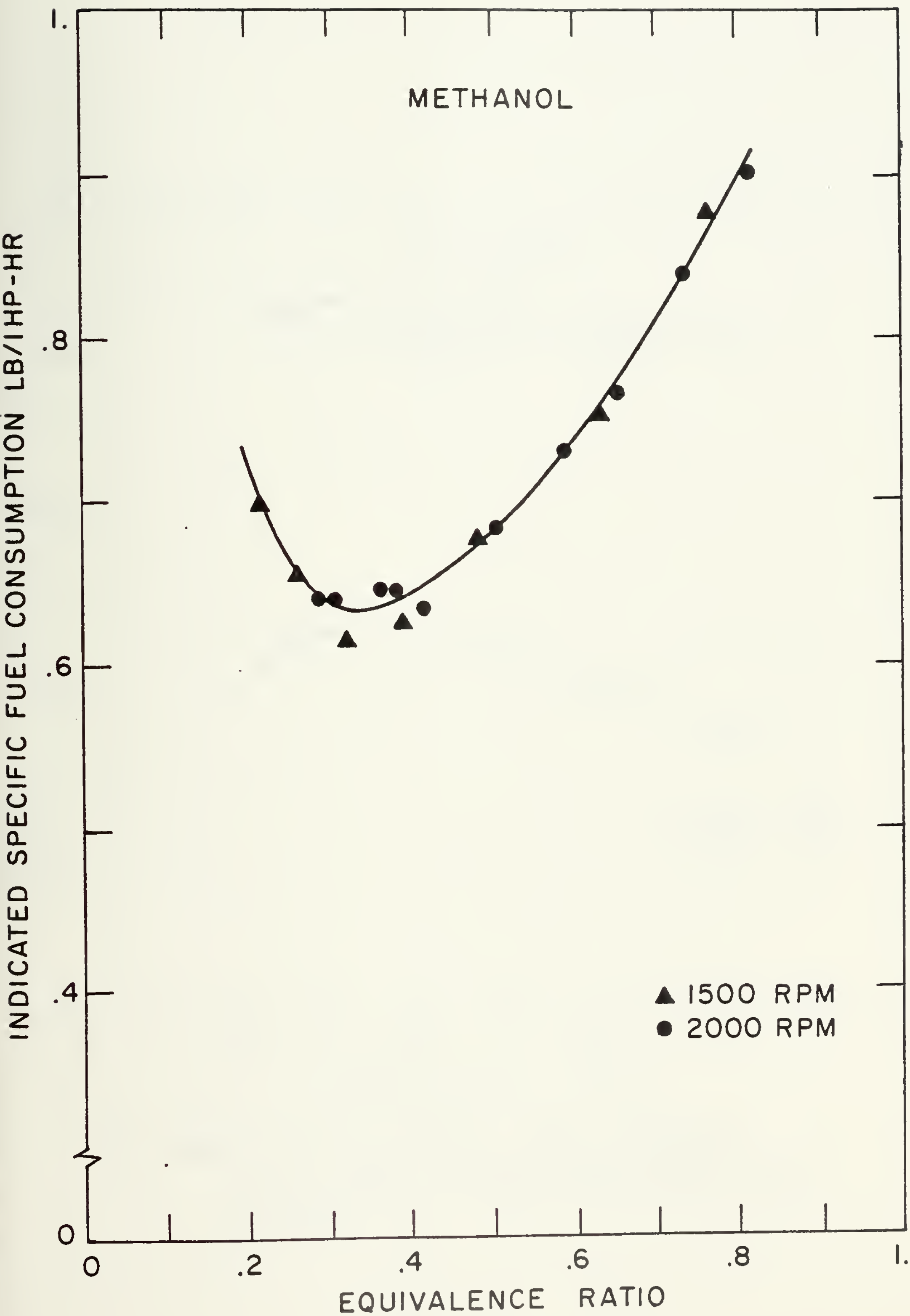


FIG. **33** INDICATED SPECIFIC FUEL CONSUMPTION FOR METHANOL

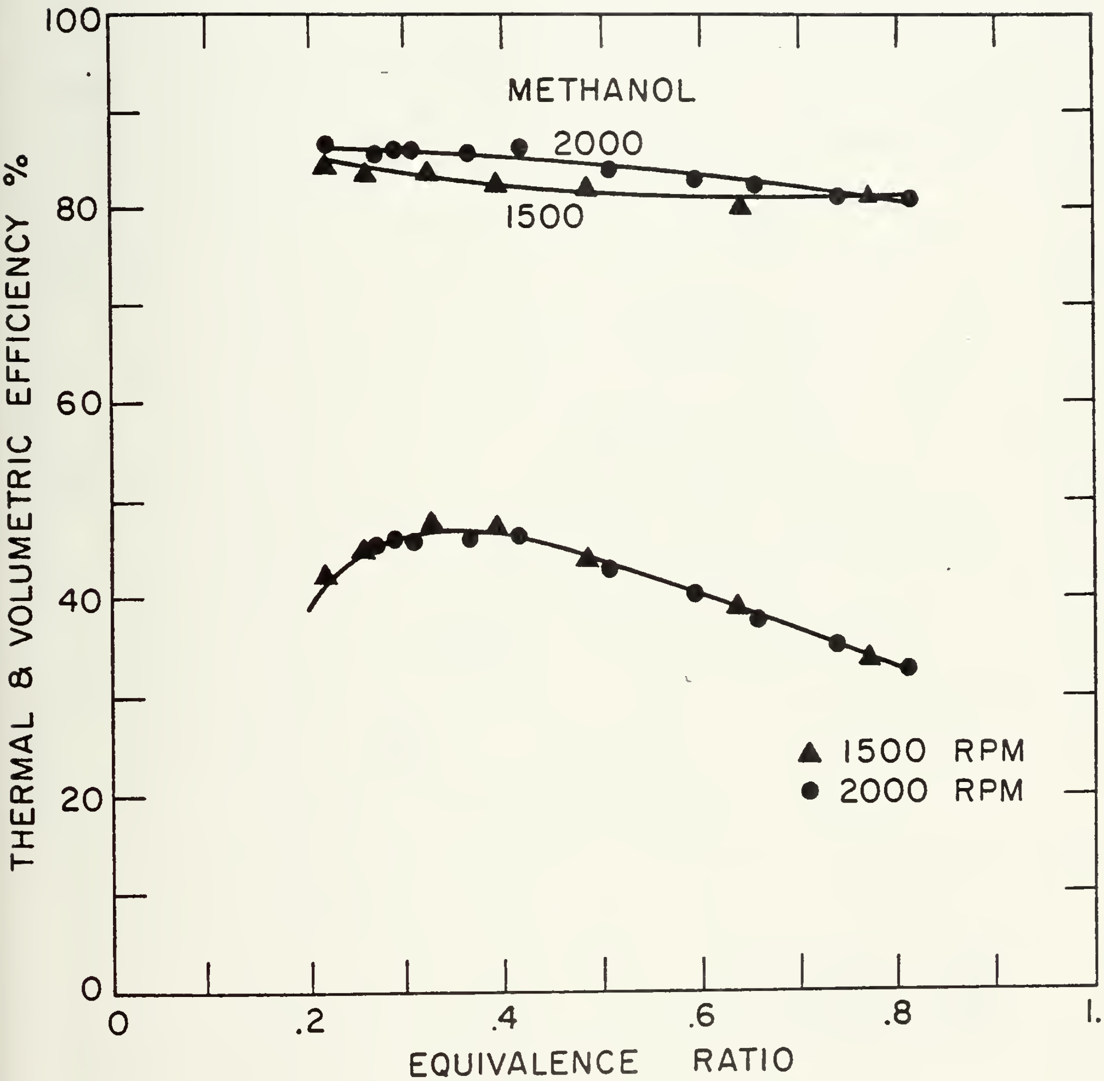


FIG. **34** INDICATED THERMAL AND VOLUMETRIC EFFICIENCY VS EQUIVALENCE RATIO FOR METHANOL

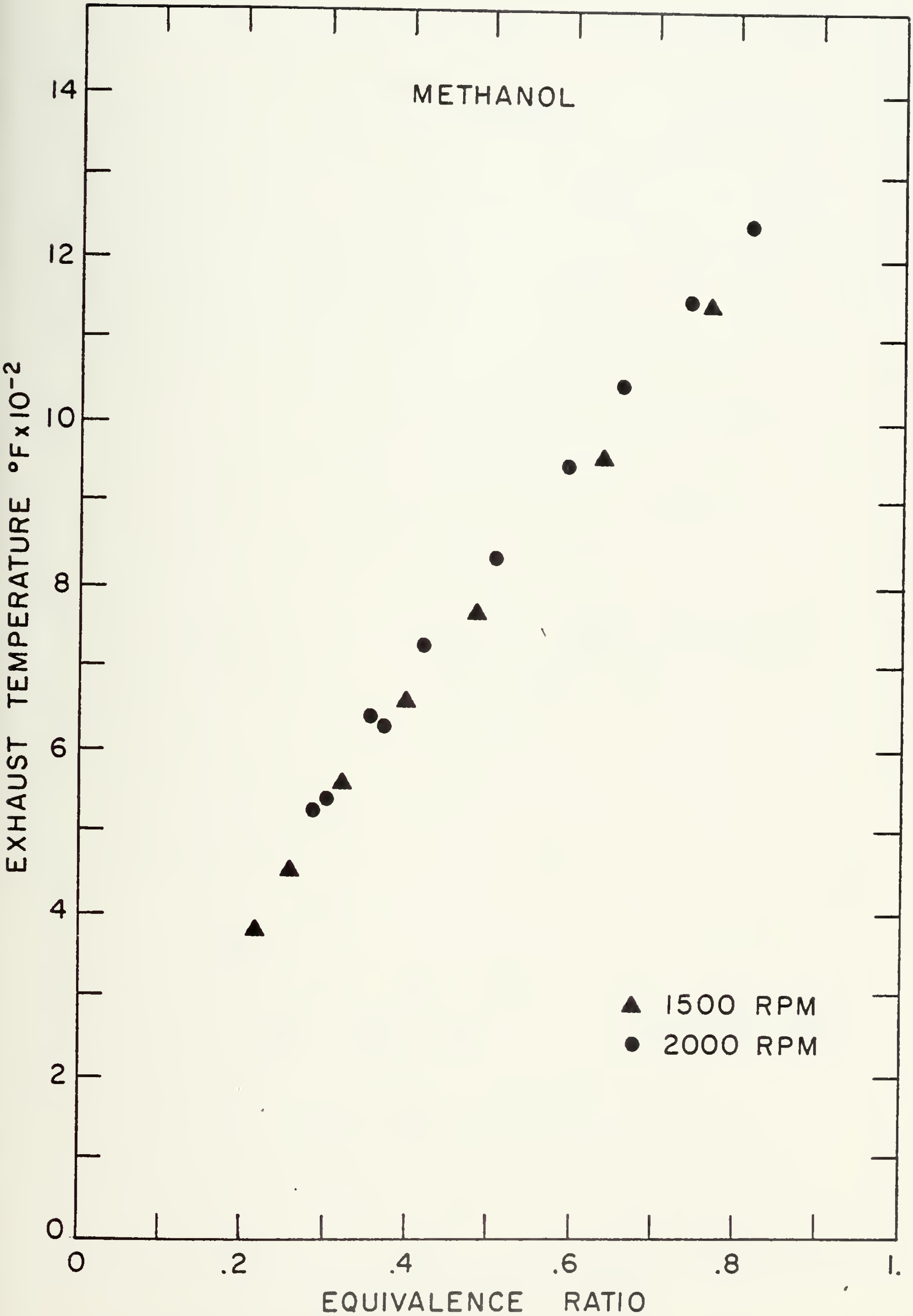


FIG. **35** EXHAUST TEMPERATURE VS EQUIVALENCE RATIO FOR METHANOL

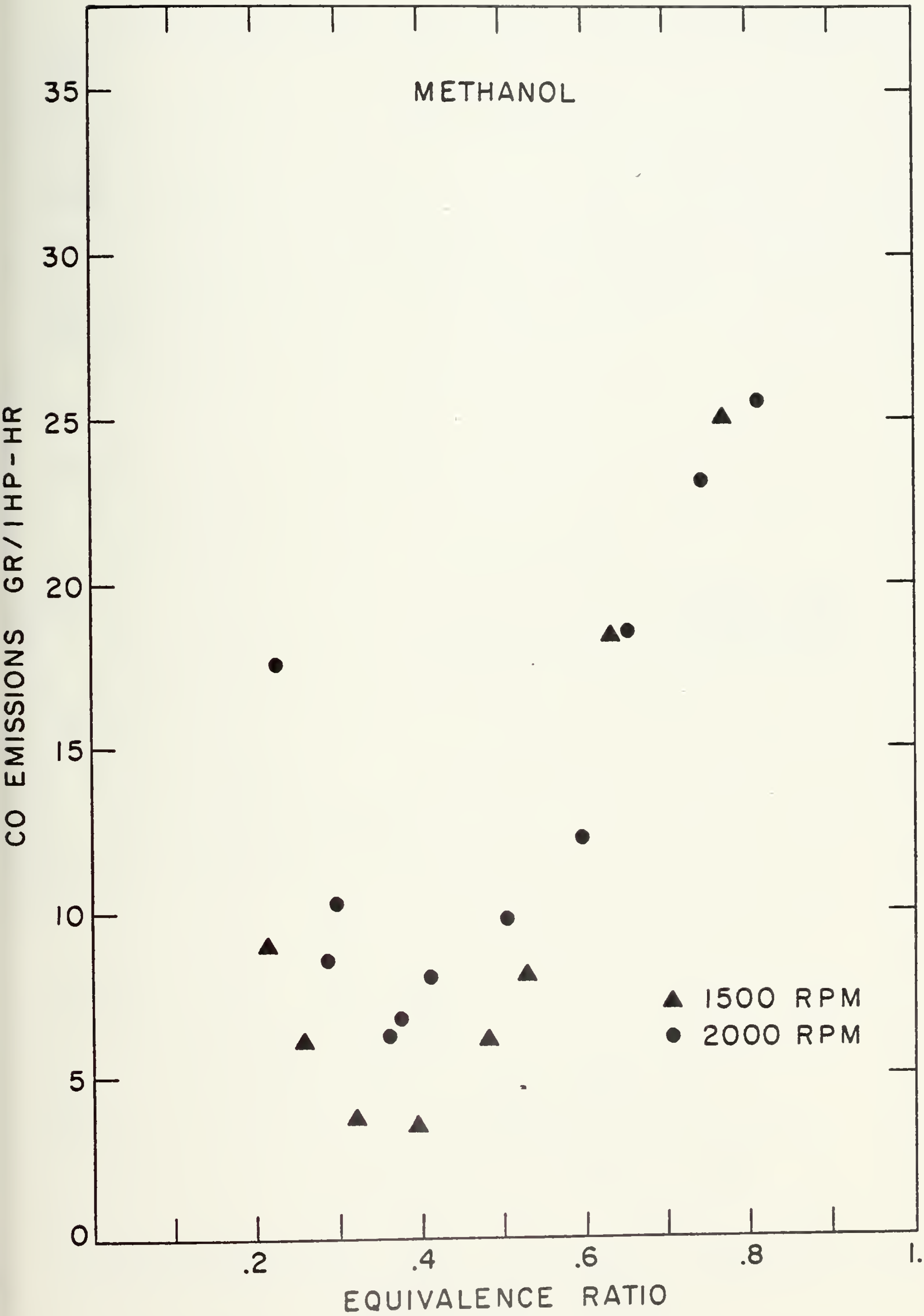


FIG. 36 CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

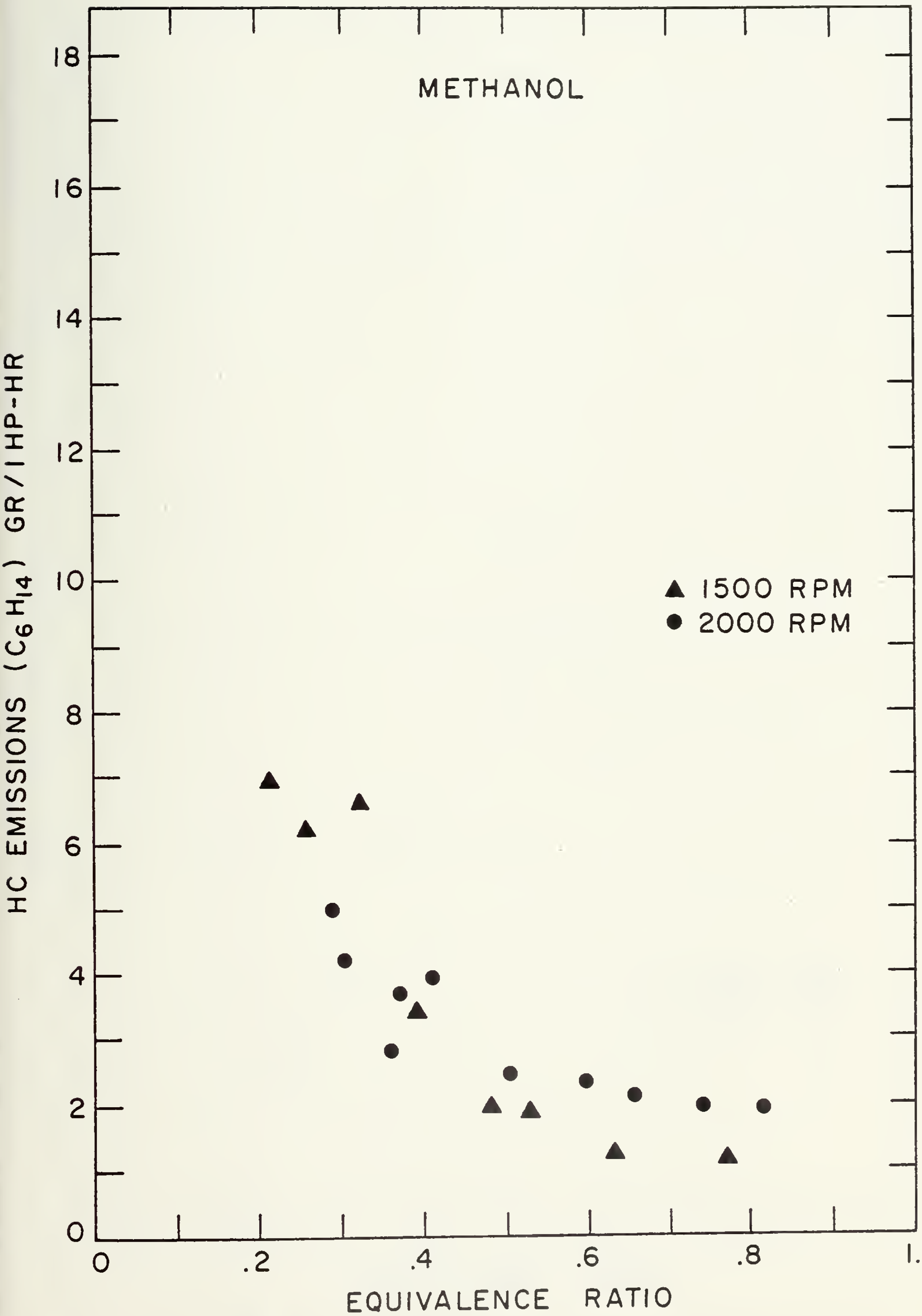


FIG. **37** HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

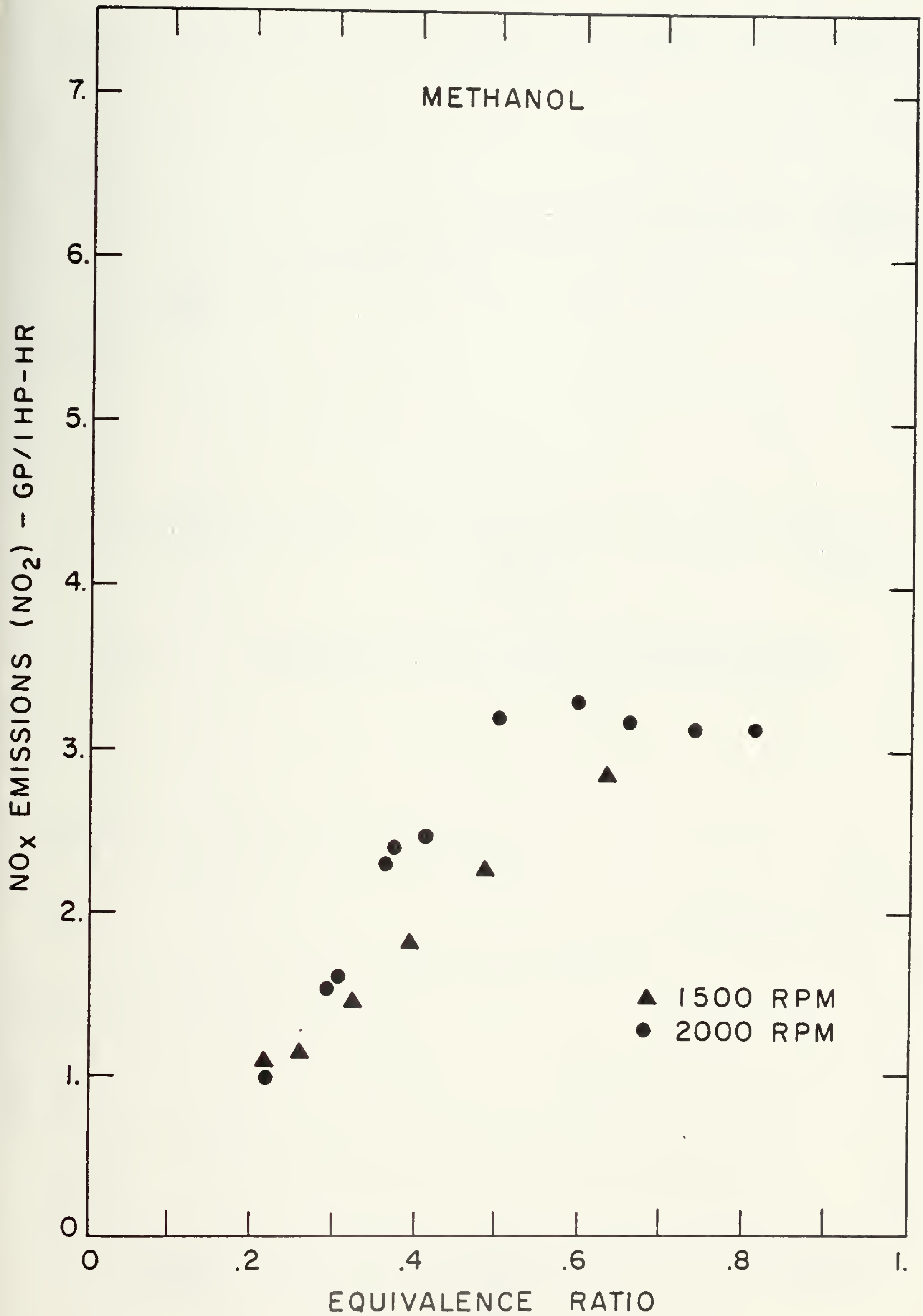


FIG. 38 NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

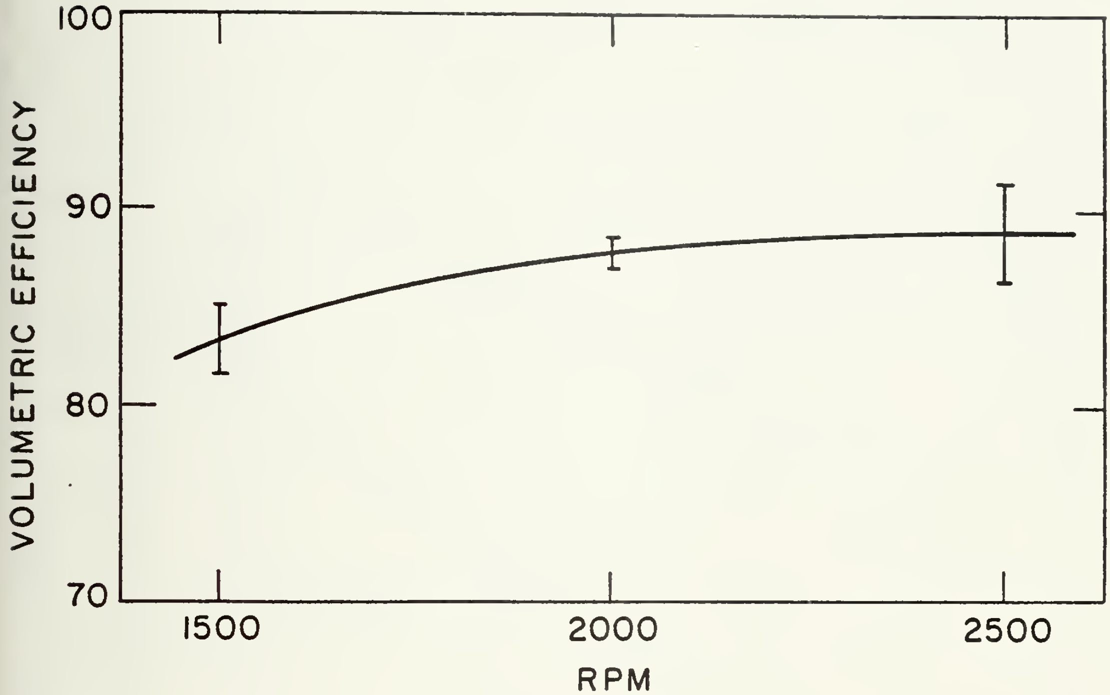


Fig. Volumetric Efficiency vs Engine RPM

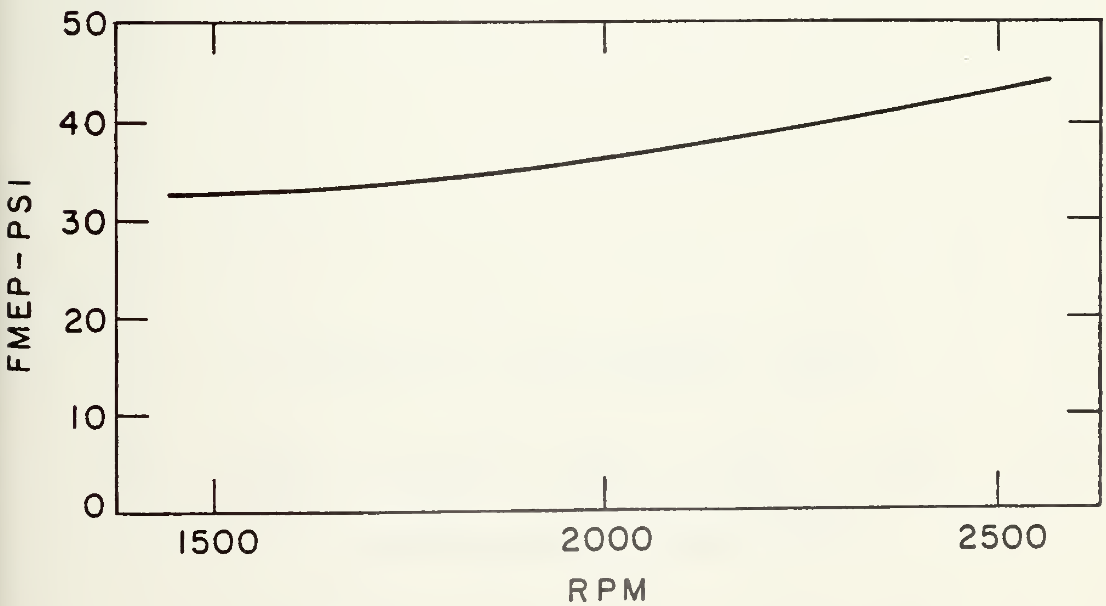


Fig. 39 Friction Mean Effective Pressure vs Engine RPM

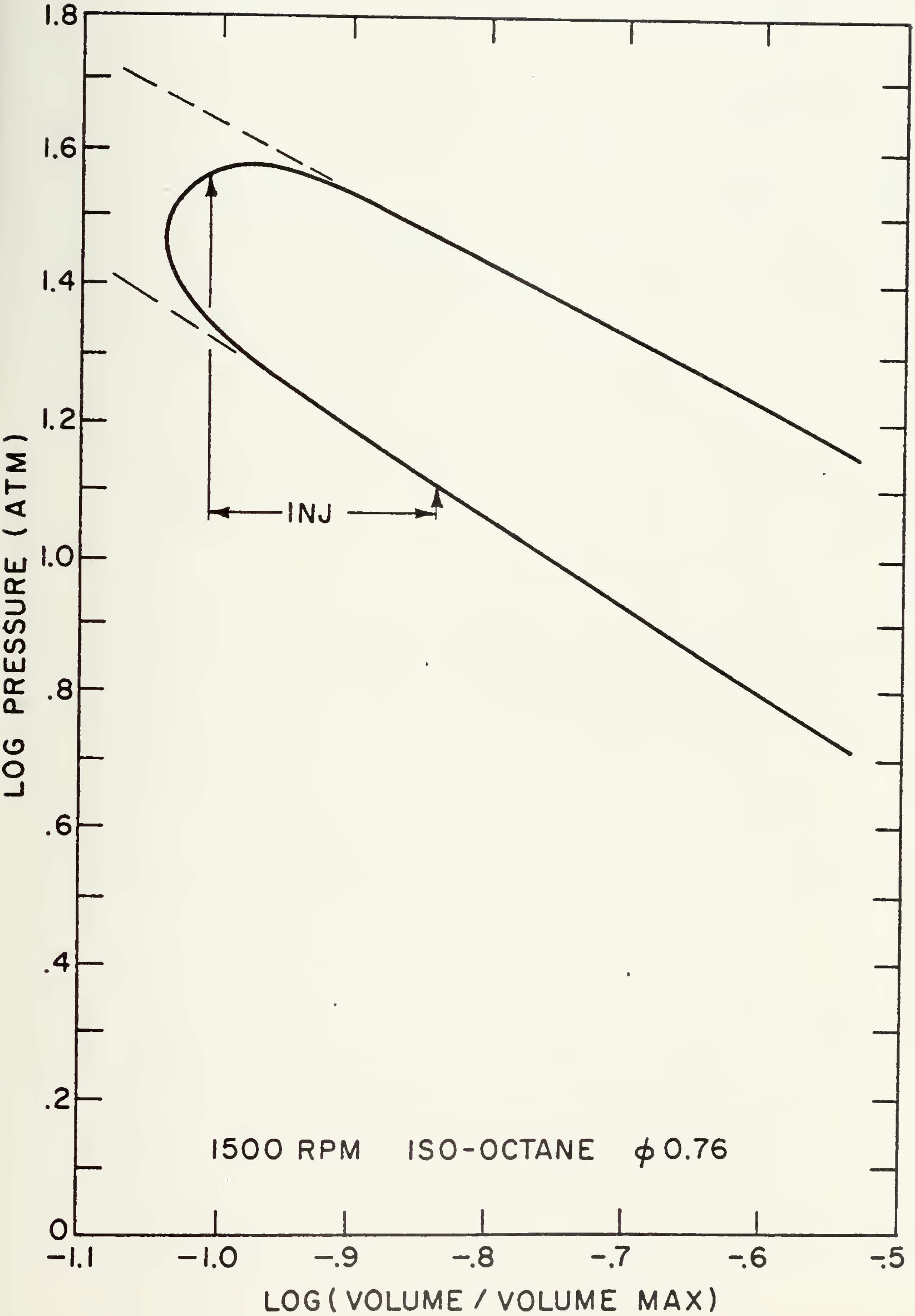


FIG. **40** LOG P VS LOG V FOR ISO-OCTANE, ϕ = 0.76, 2500 RPM

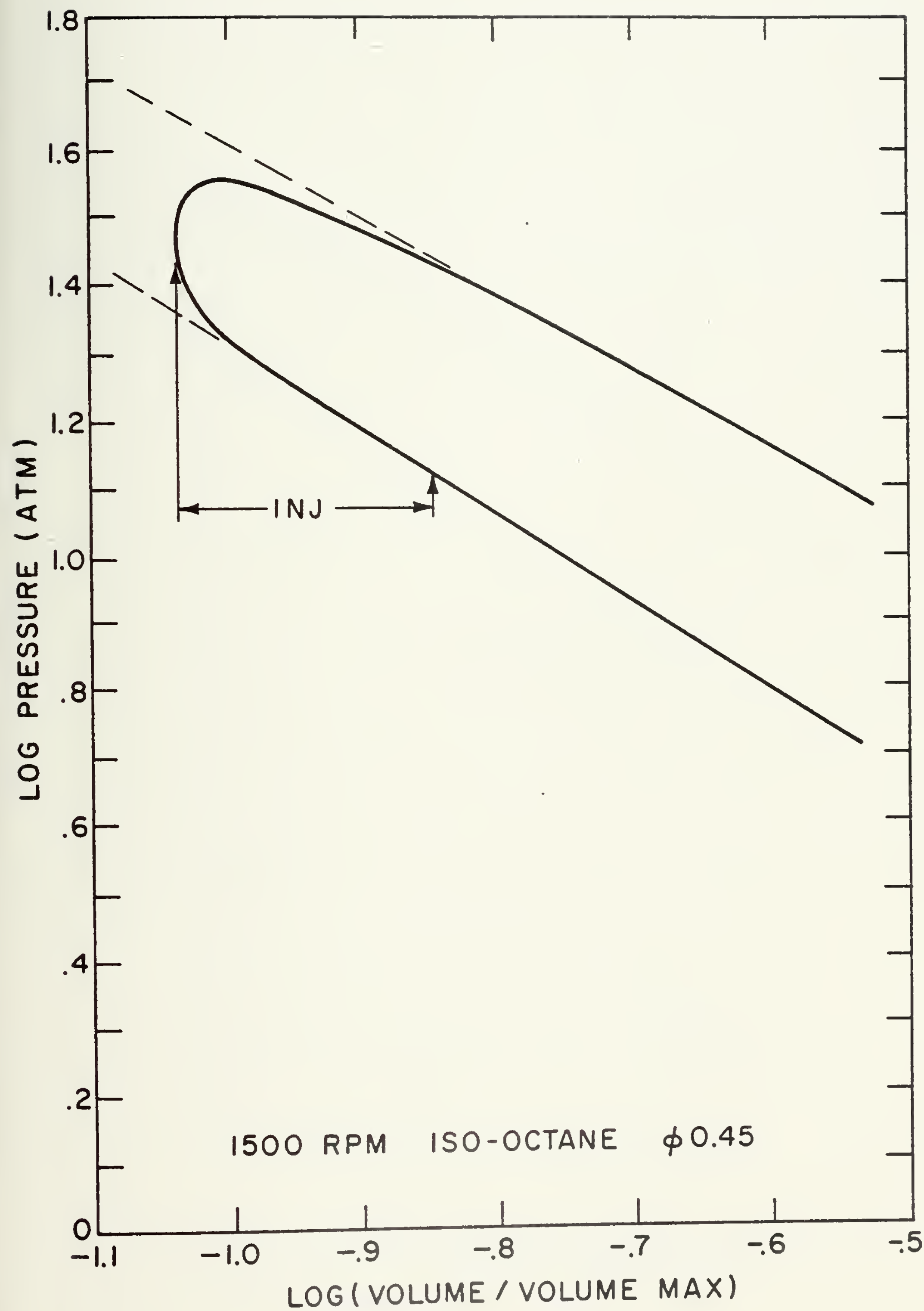


FIG. 41 LOG P VS LOG V FOR ISO-OCTANE, ϕ = 0.45, 1500 RPM

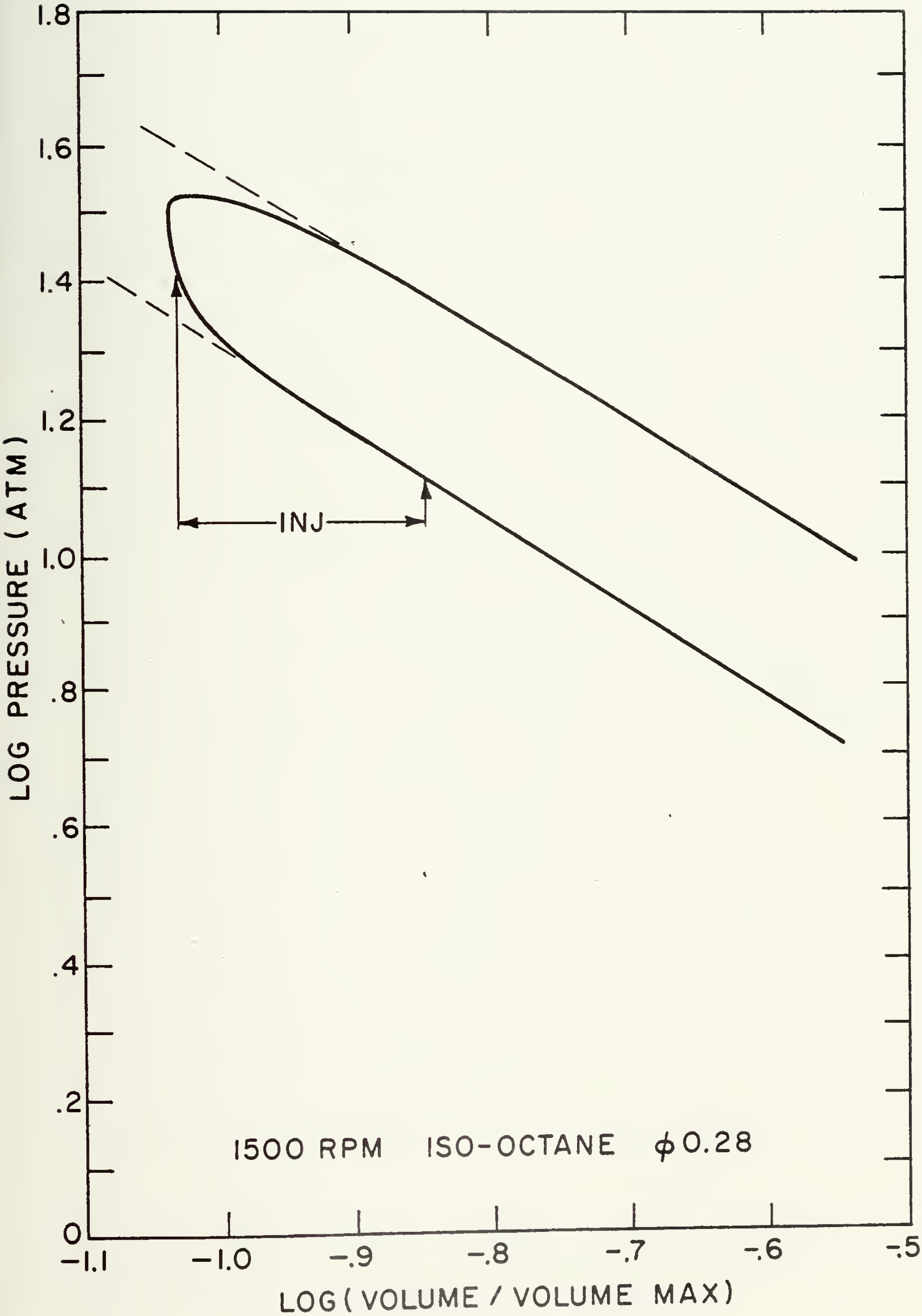


FIG. **42** LOG P VS LOG V FOR ISO-OCTANE,
ϕ = 0.28, 1500 RPM

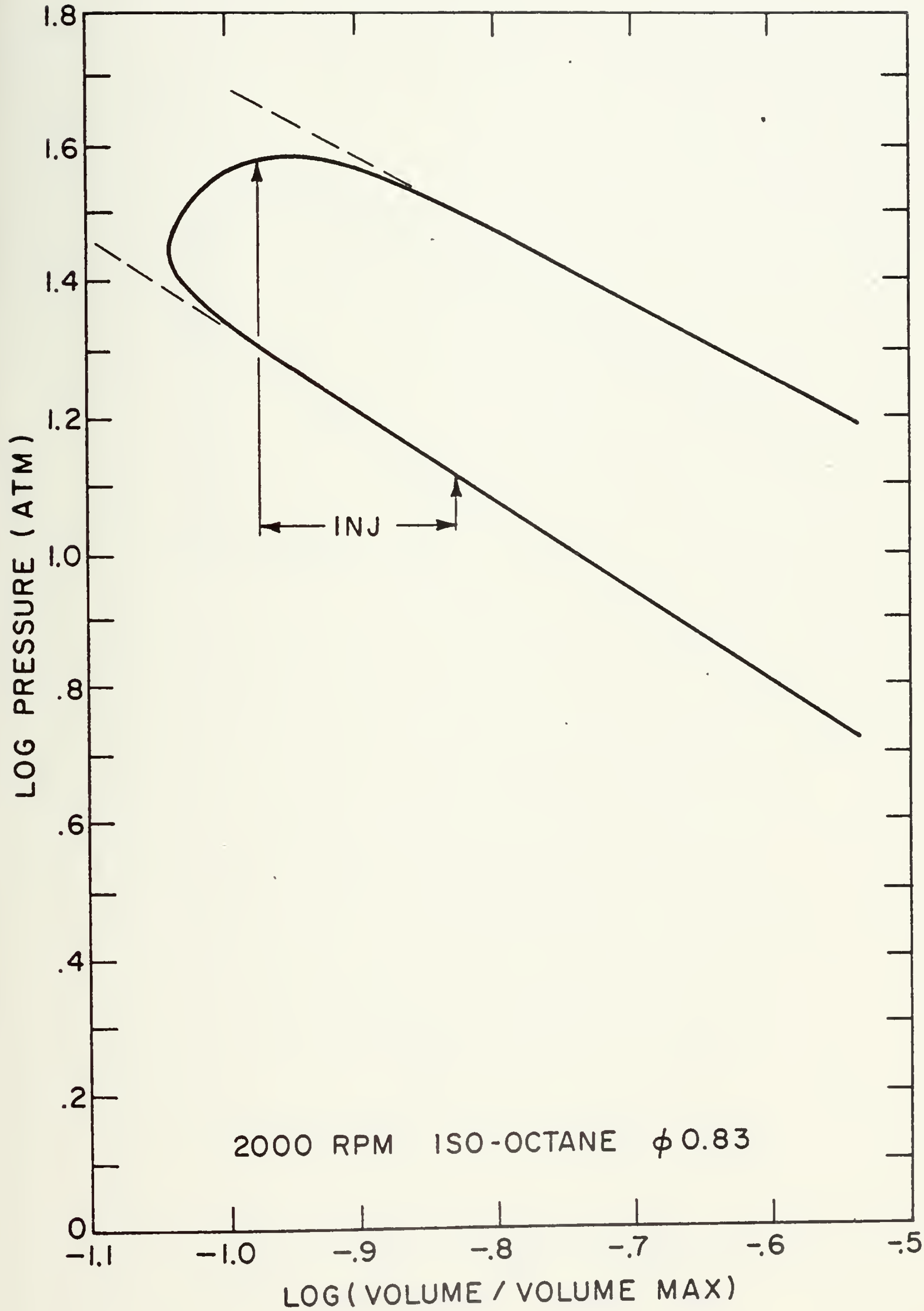


FIG. 43 LOG P VS LOG V FOR ISO-OCTANE,
Φ = 0.83, 2000 RPM

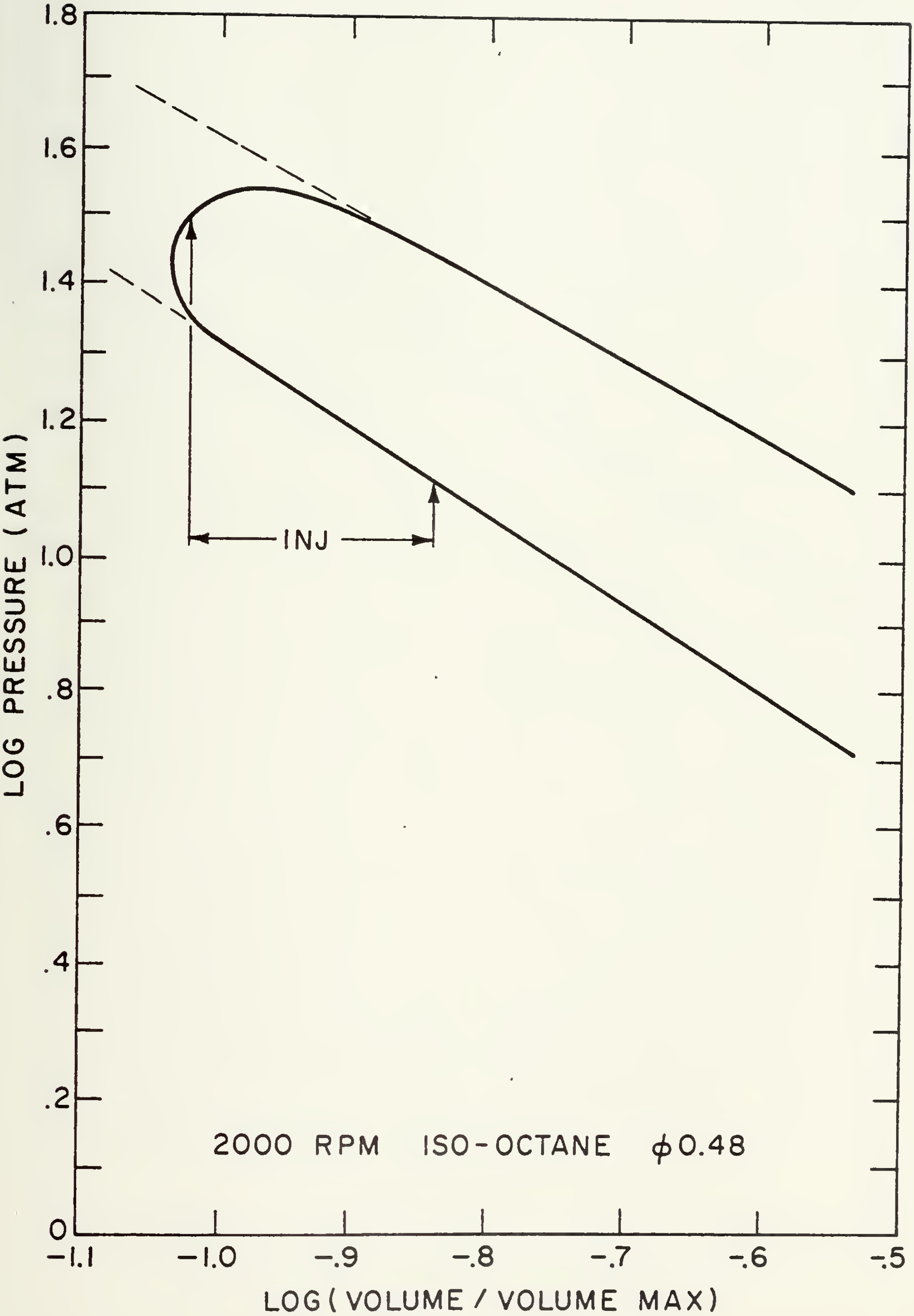


FIG. 44 LOG P. VS LOG V FOR ISO-OCTANE, $\phi = 0.48$, 2000 RPM

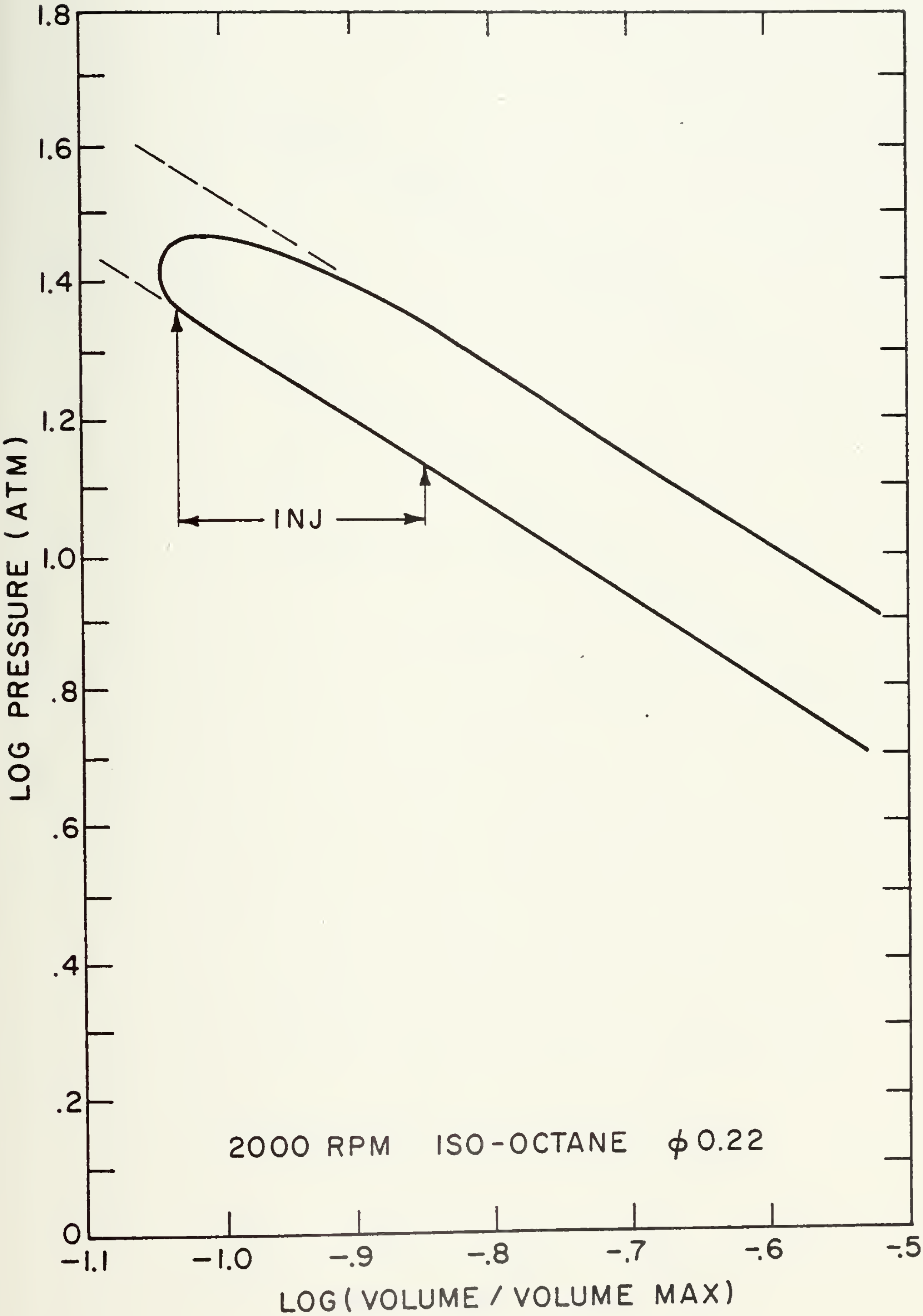


FIG. 45 LOG P VS LOG V FOR ISO-OCTANE, ϕ = 0.22, 2000 RPM

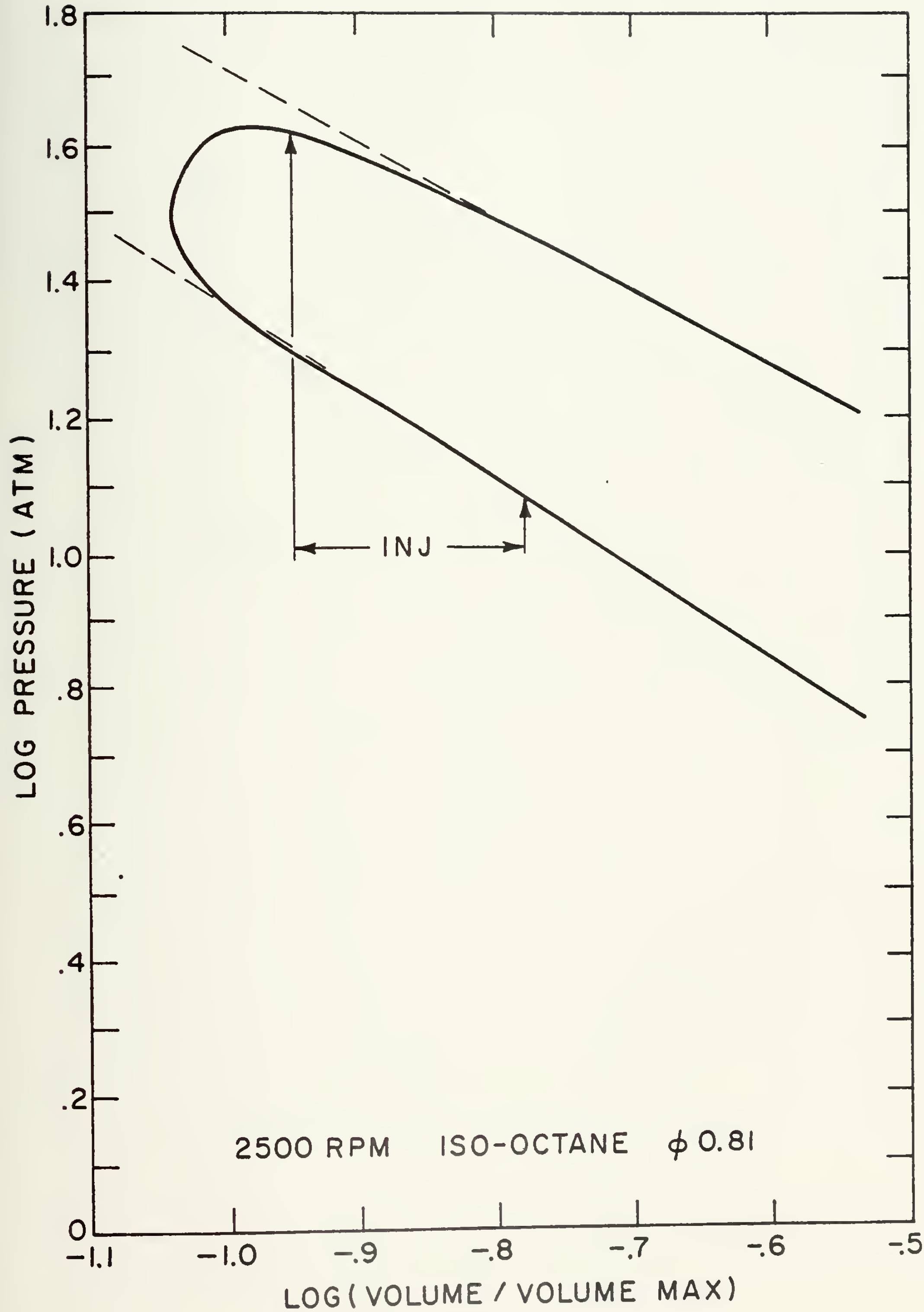


FIG. 46 LOG P VS LOG V FOR ISO-OCTANE, $\phi = 0.81$, 2500 RPM

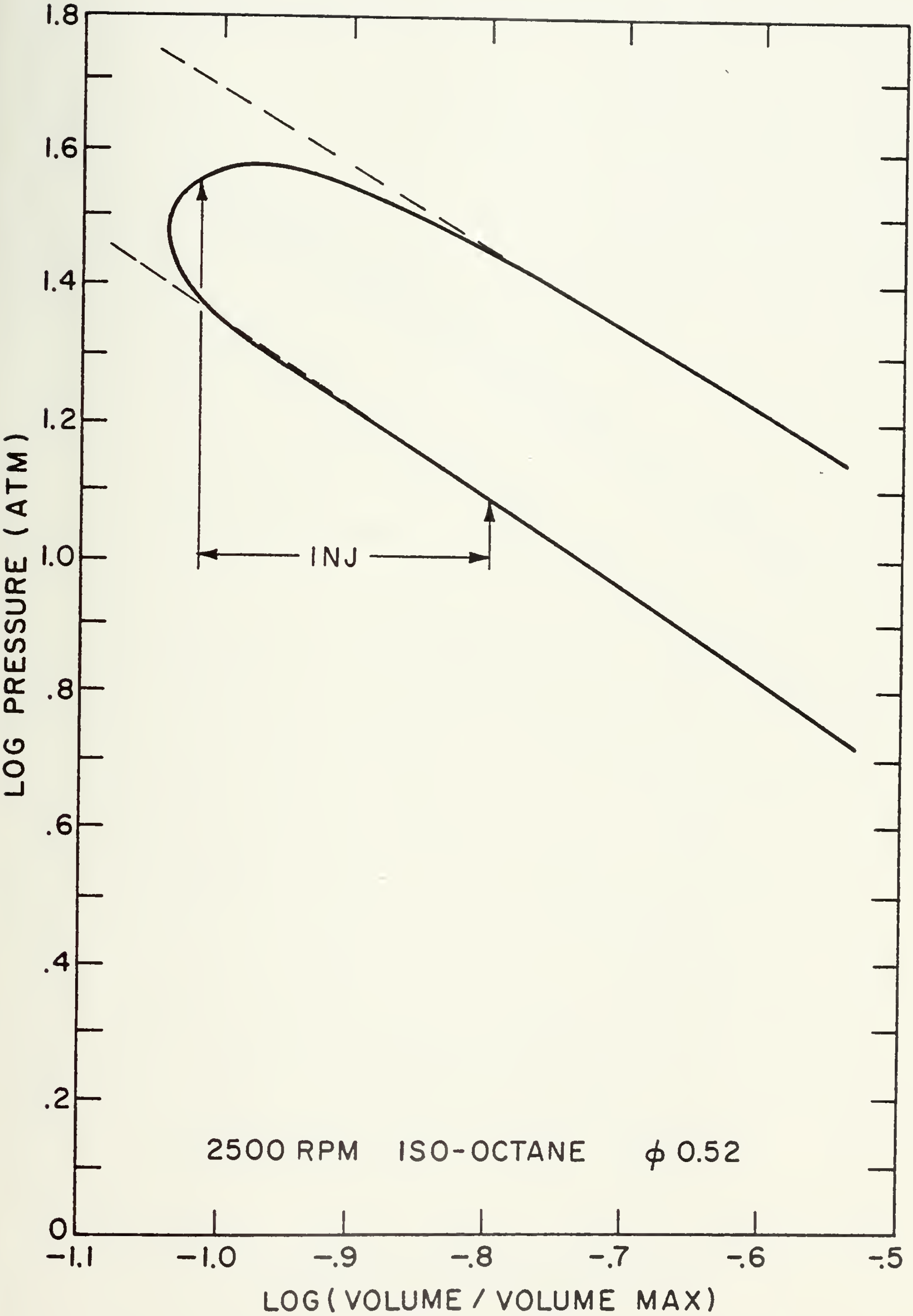


FIG. 47 LOG P VS LOG V FOR ISO-OCTANE,
ϕ = 0.52, RPM

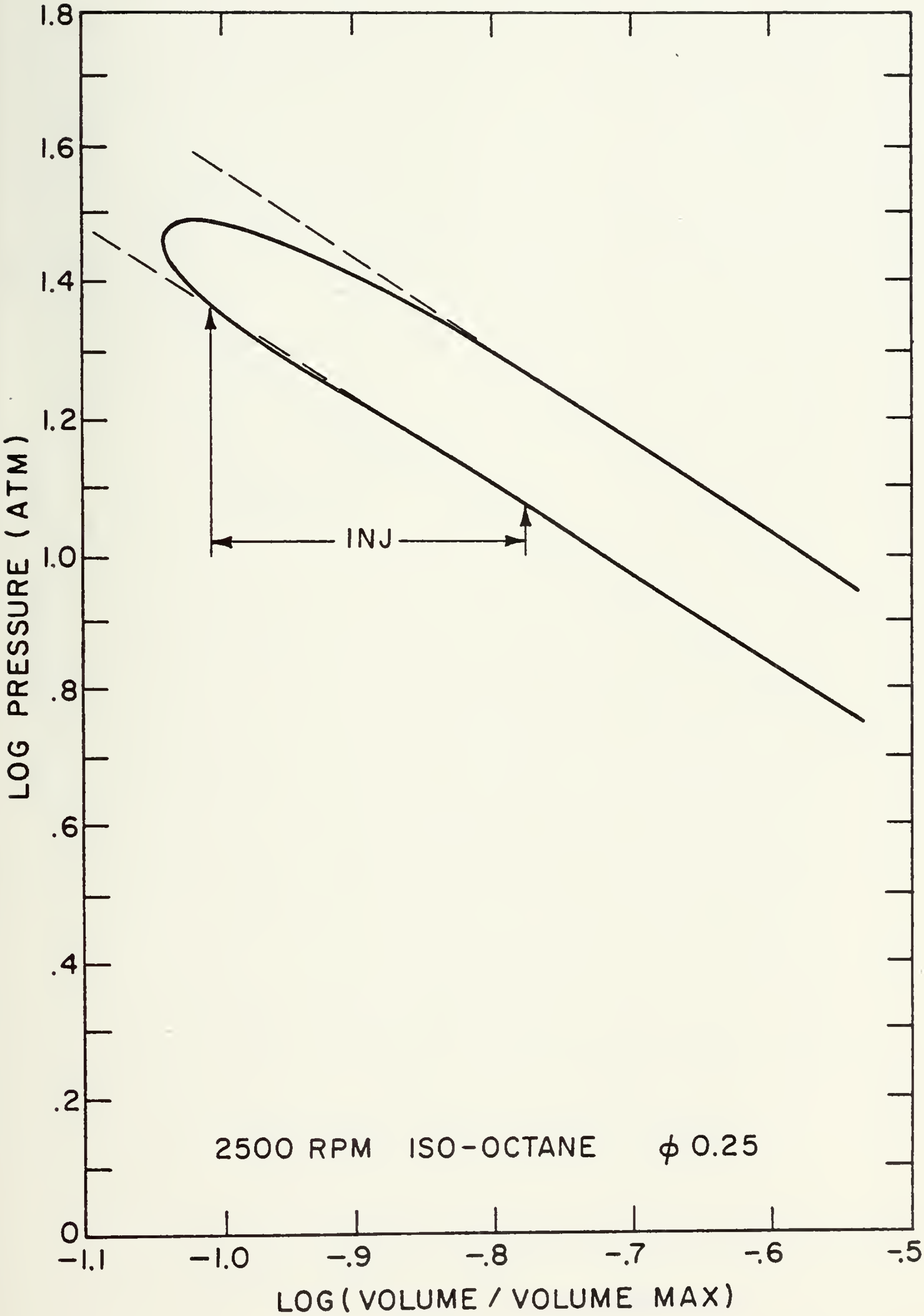


FIG. **48** LOG P VS LOG V FOR ISO-OCTANE, $\phi = 0.25$, 2500 RPM

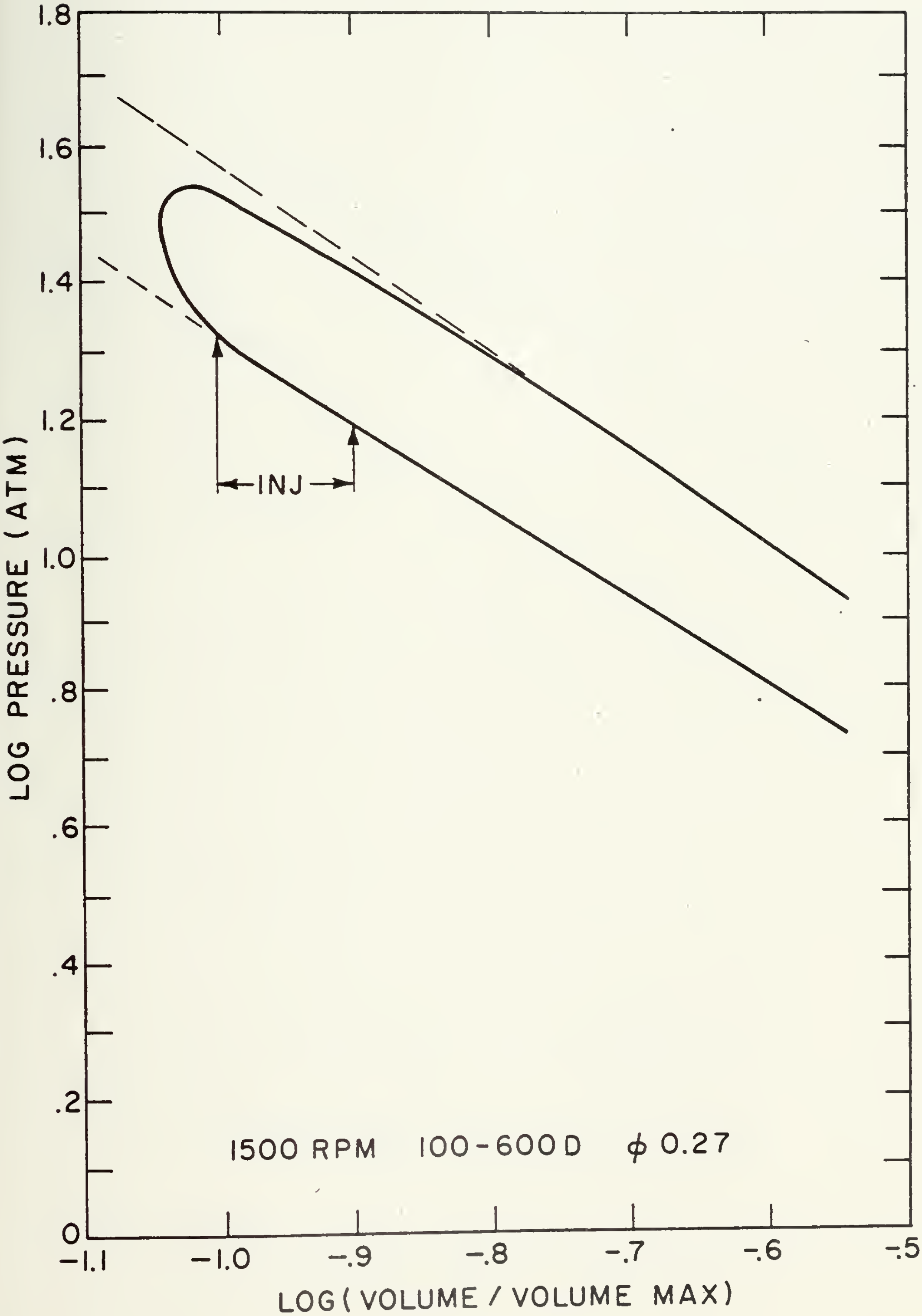


FIG. **49** LOG P VS LOG V FOR 100-600, ϕ = 0.77, 1500 RPM

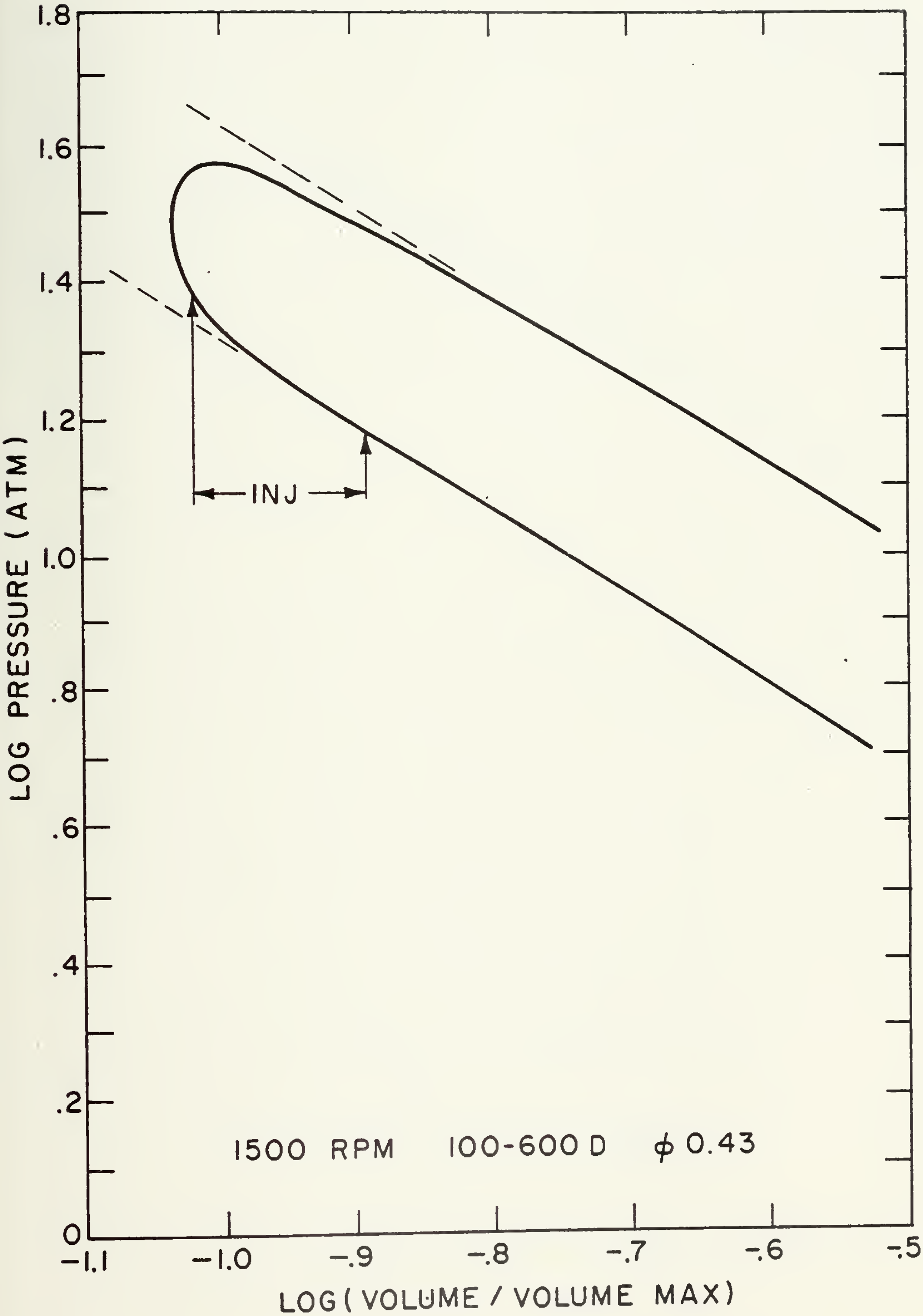


FIG. **50** LOG P VS LOG V FOR 100-600, ϕ = 0.43, 1500 RPM

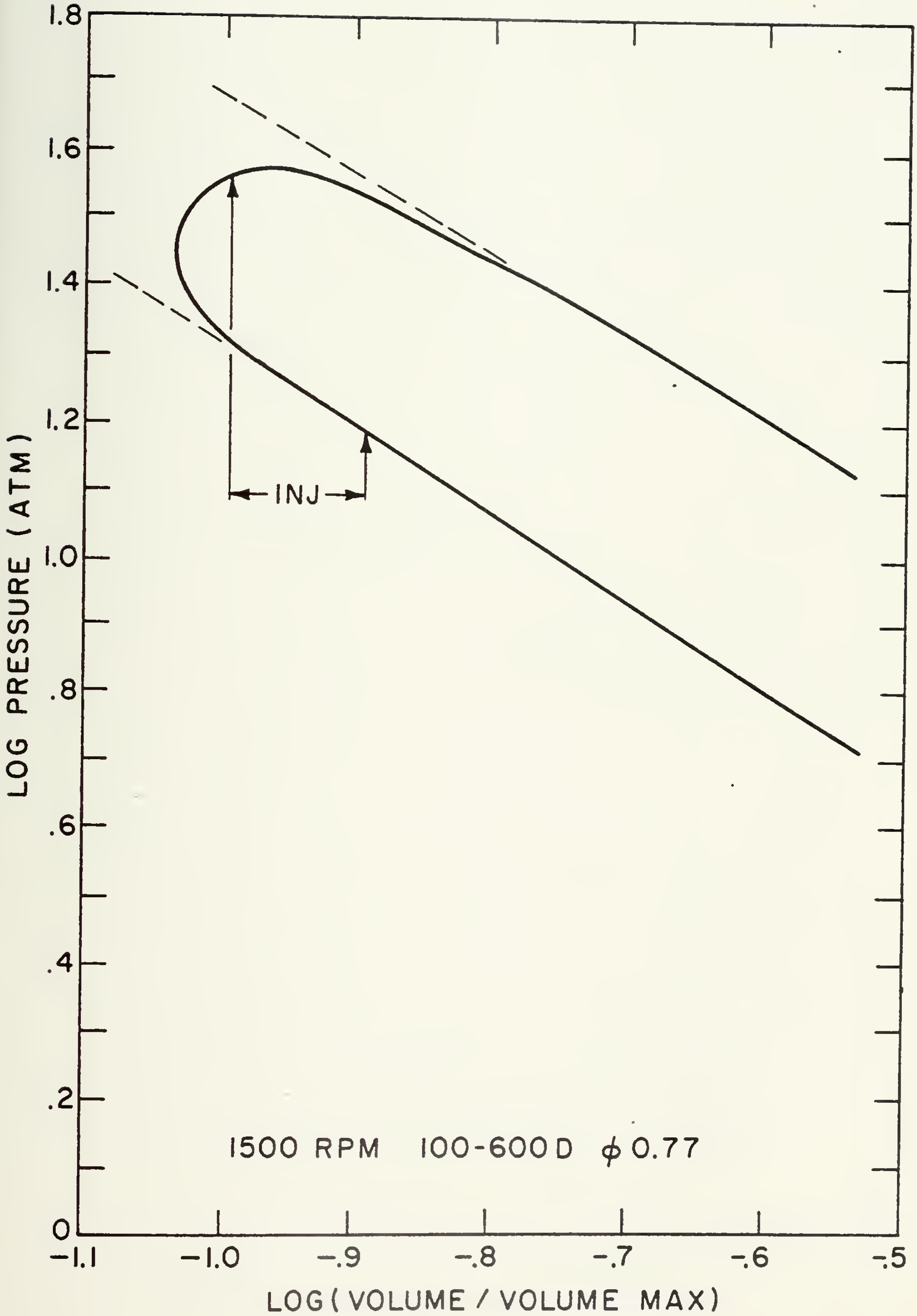


FIG. 51 LOG P VS LOG V FOR 100-600, $\phi = 0.27$, 1500 RPM

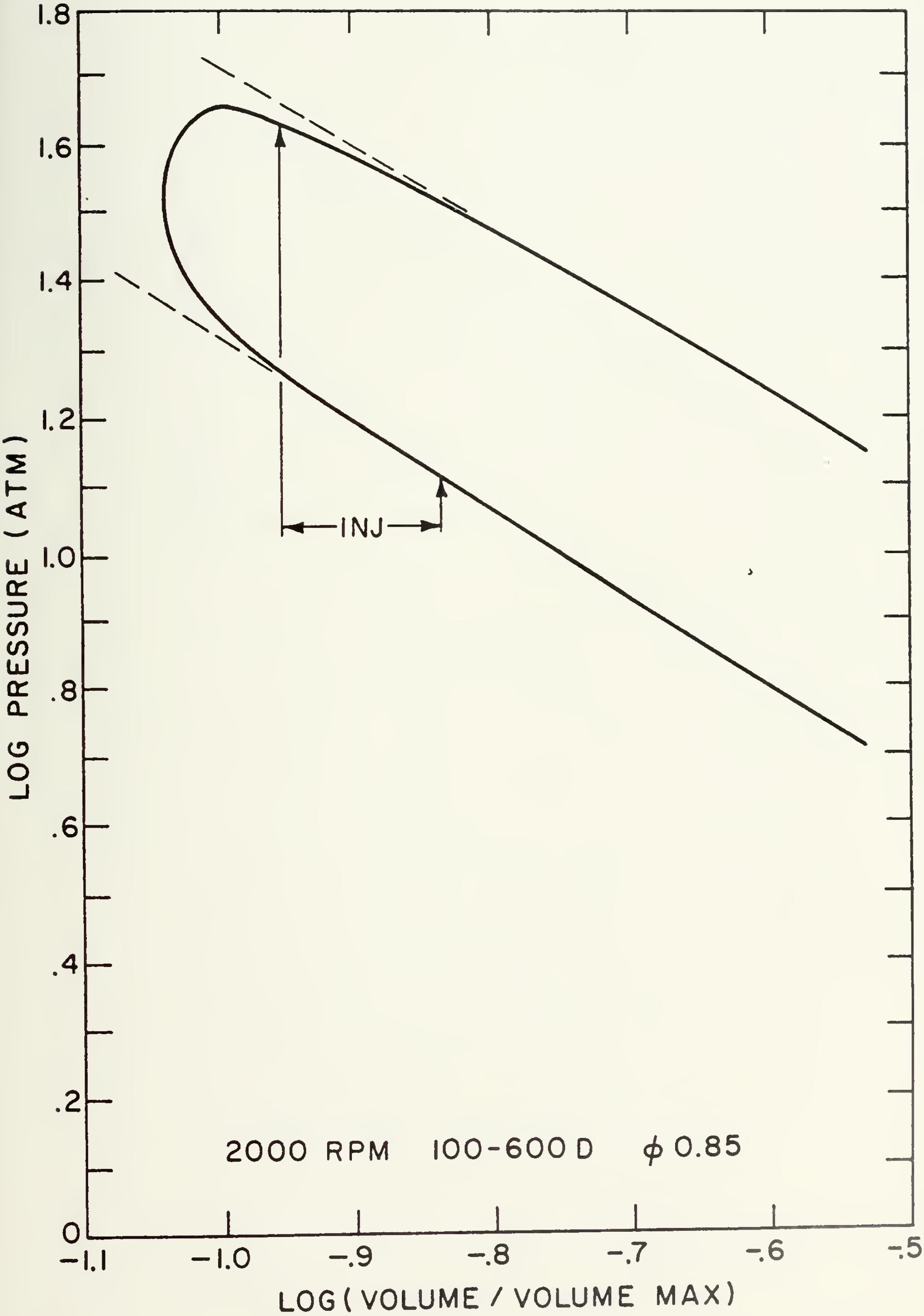


FIG. 52 LOG P VS LOG V FOR 100-600, ϕ = 0.85, 2000 RPM

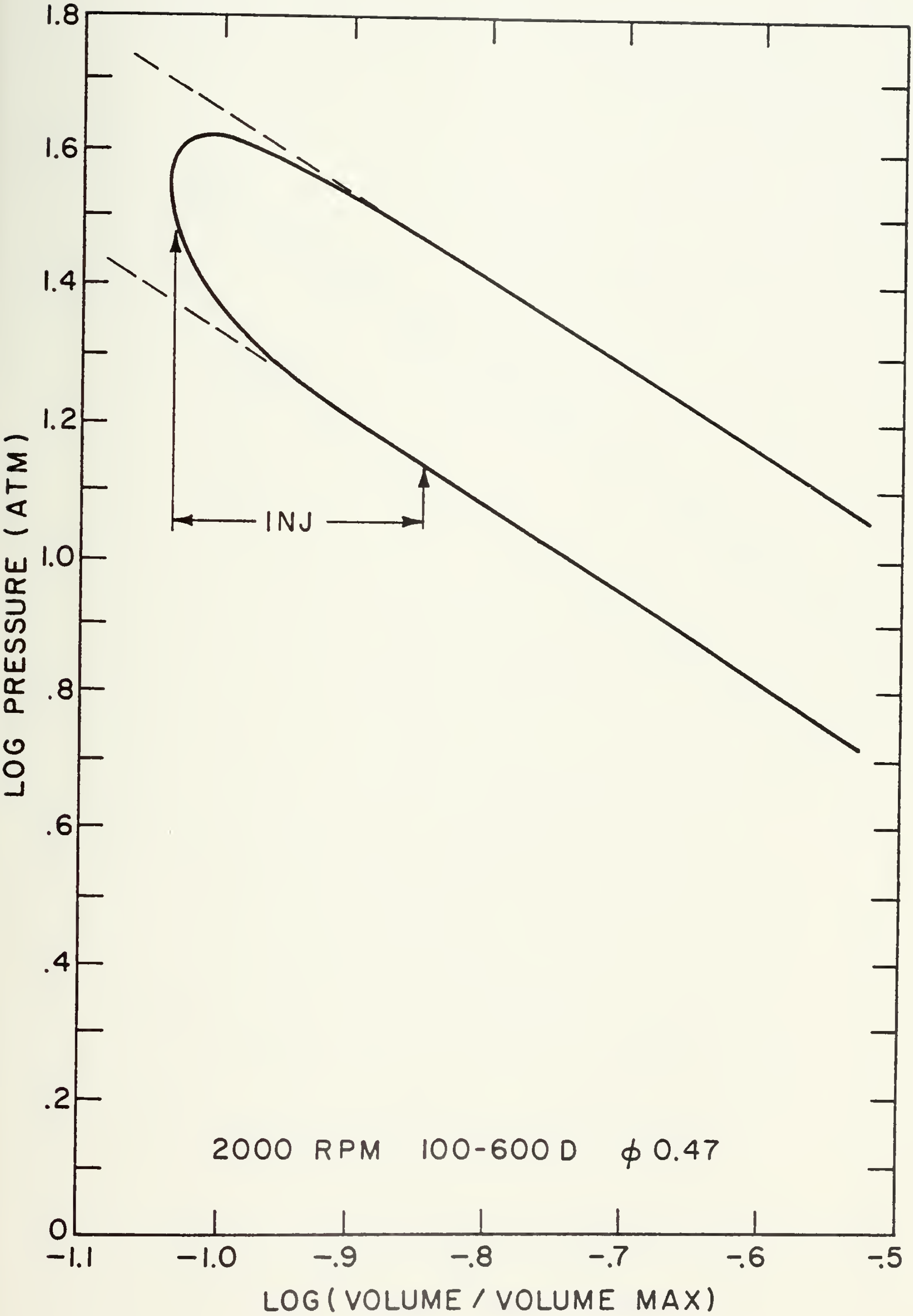


FIG. 53 LOG P VS LOG V FOR 100-600, ϕ = 0.47, RPM

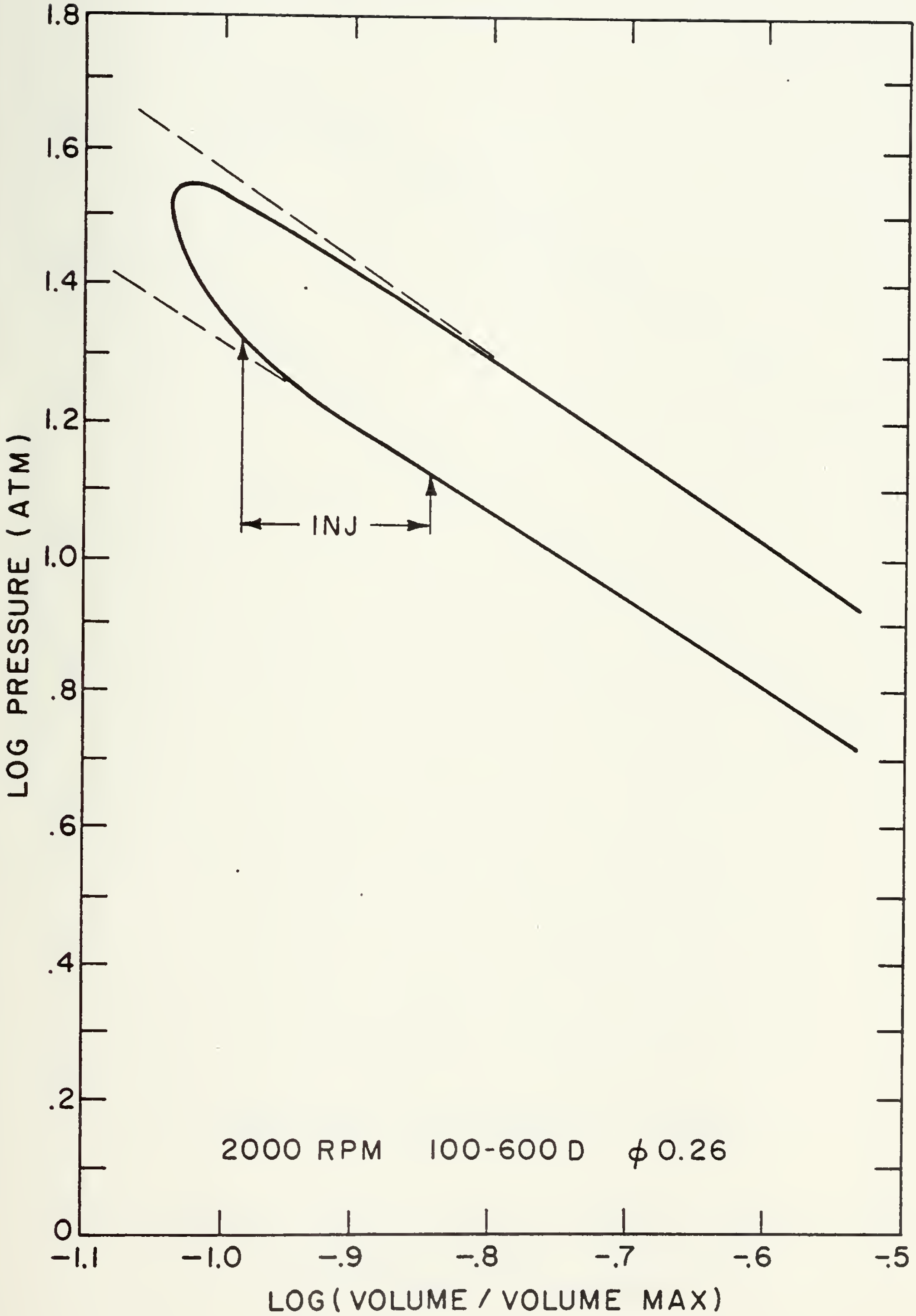


FIG. **54** LOG P VS LOG V FOR 100-600, $\phi = 0.26$, 2000 RPM

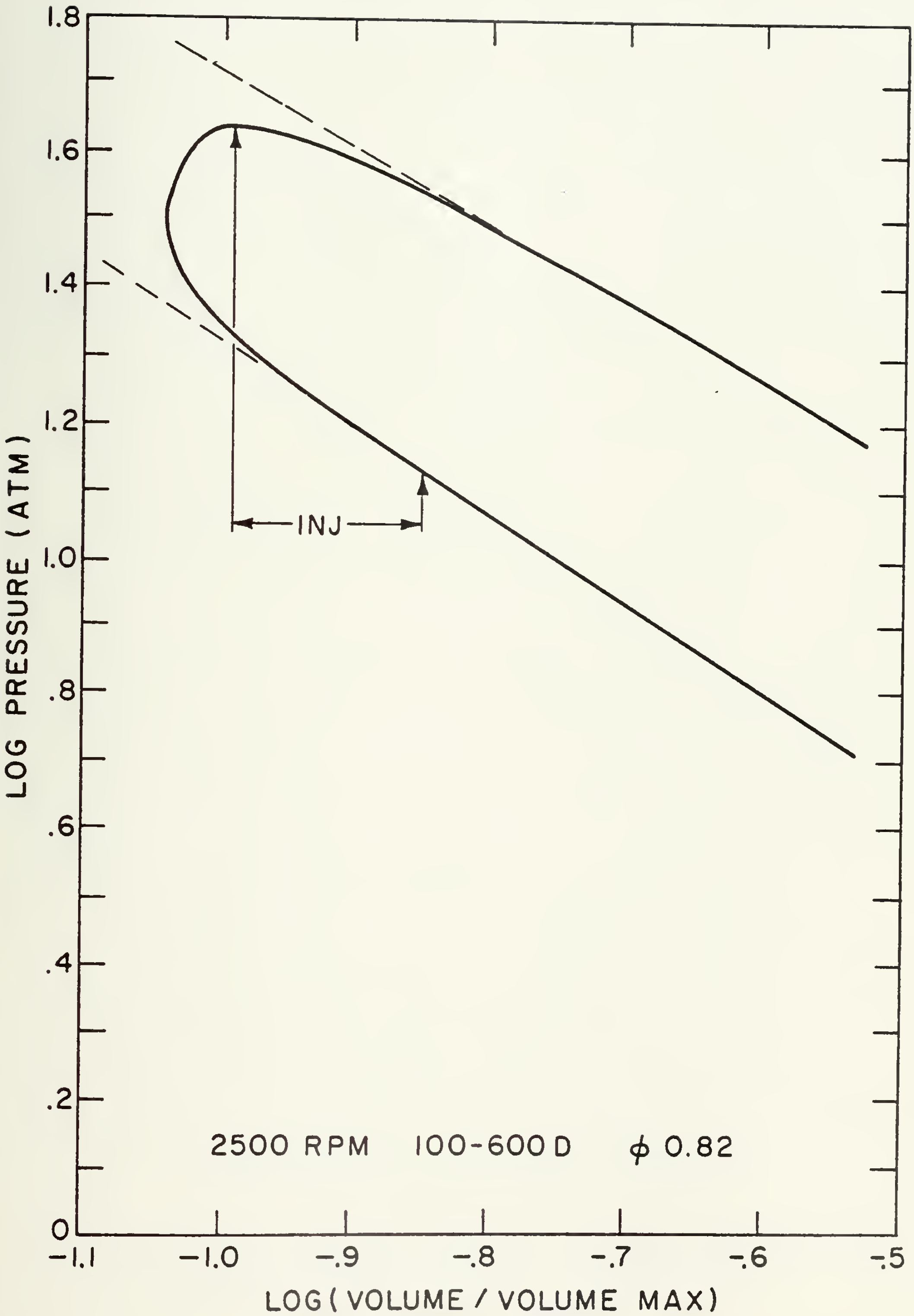


FIG. **55** LOG P VS LOG V FOR 100-600, ϕ = 0.82, 2500 RPM

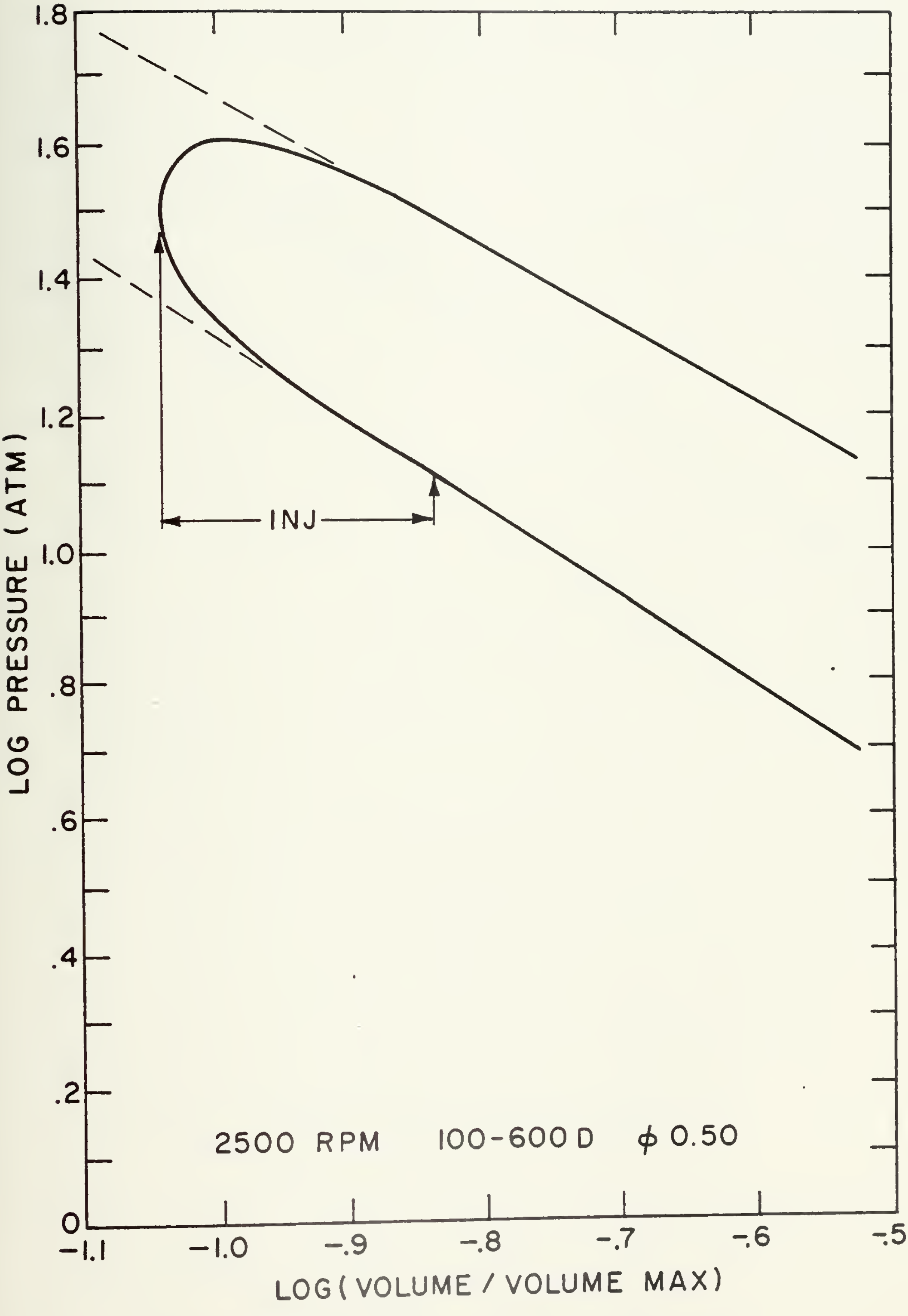


FIG. **56** LOG P VS LOG V FOR 100-600, ϕ = 0.50, 2500 RPM

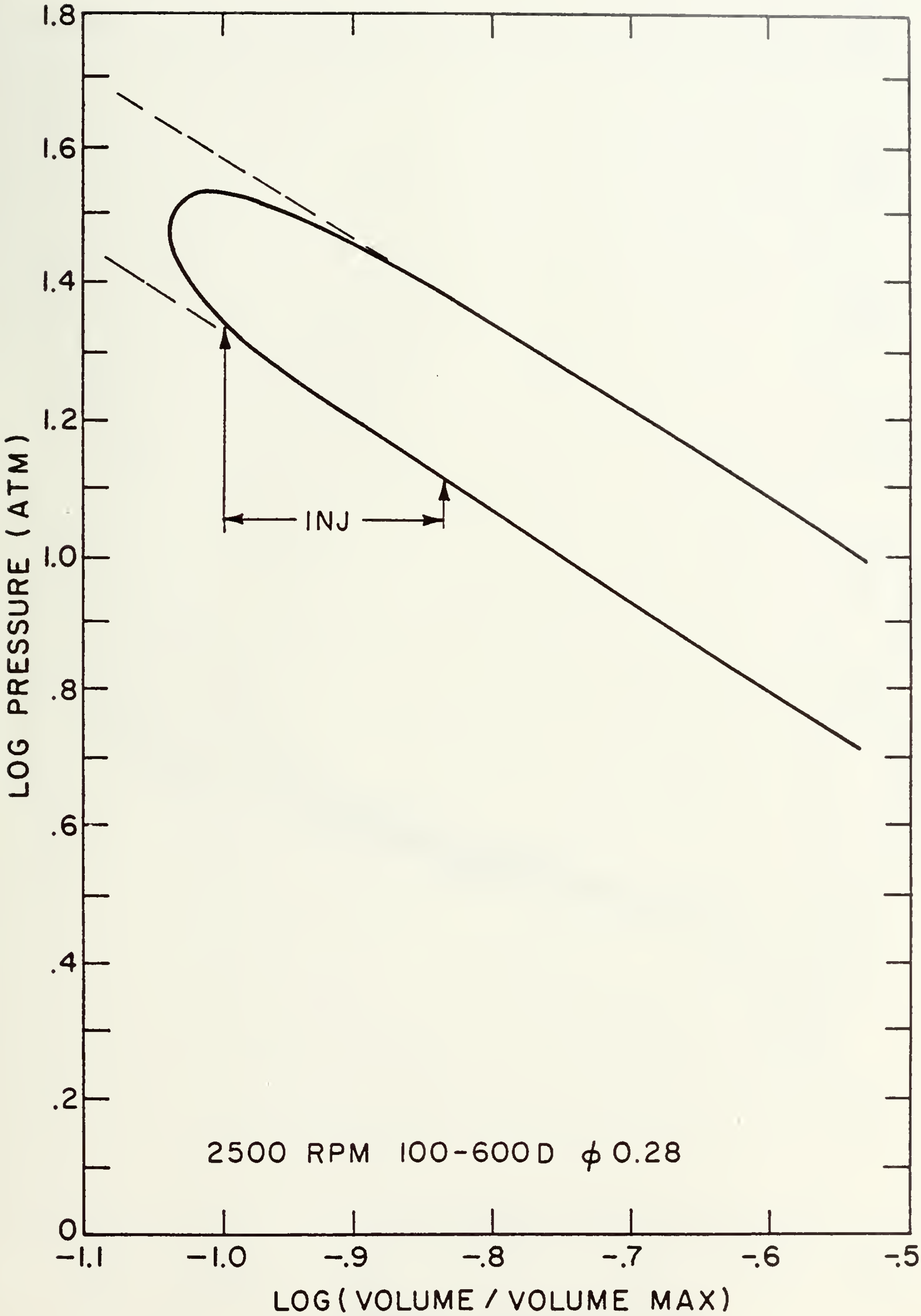


FIG. **57** LOG P VS LOG V FOR 100-600,
ϕ = 0.28, 2500 RPM

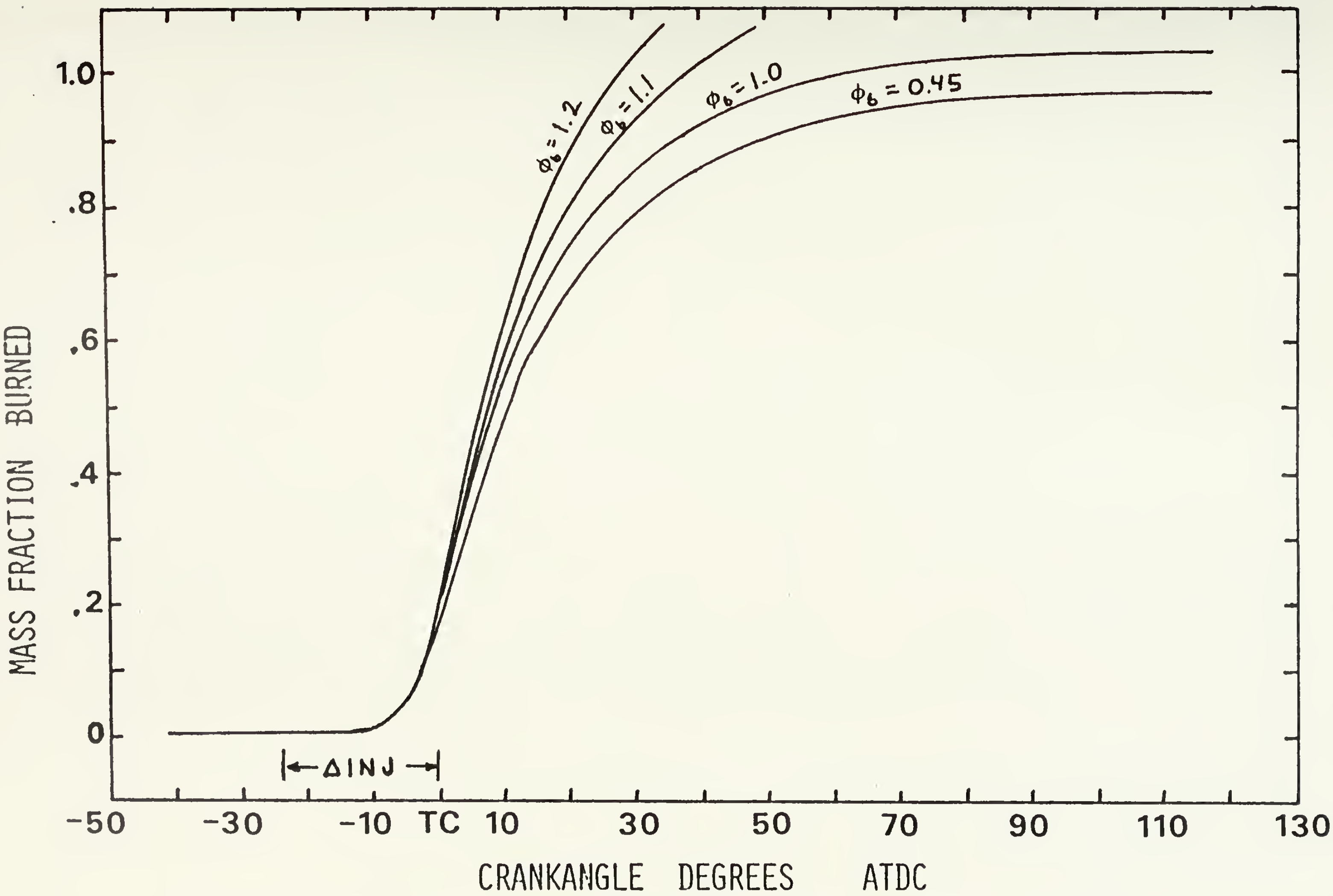


FIG. **58** FUEL MASS FRACTION BURNT VS CRANKANGLE FOR FIXED ϕ_B

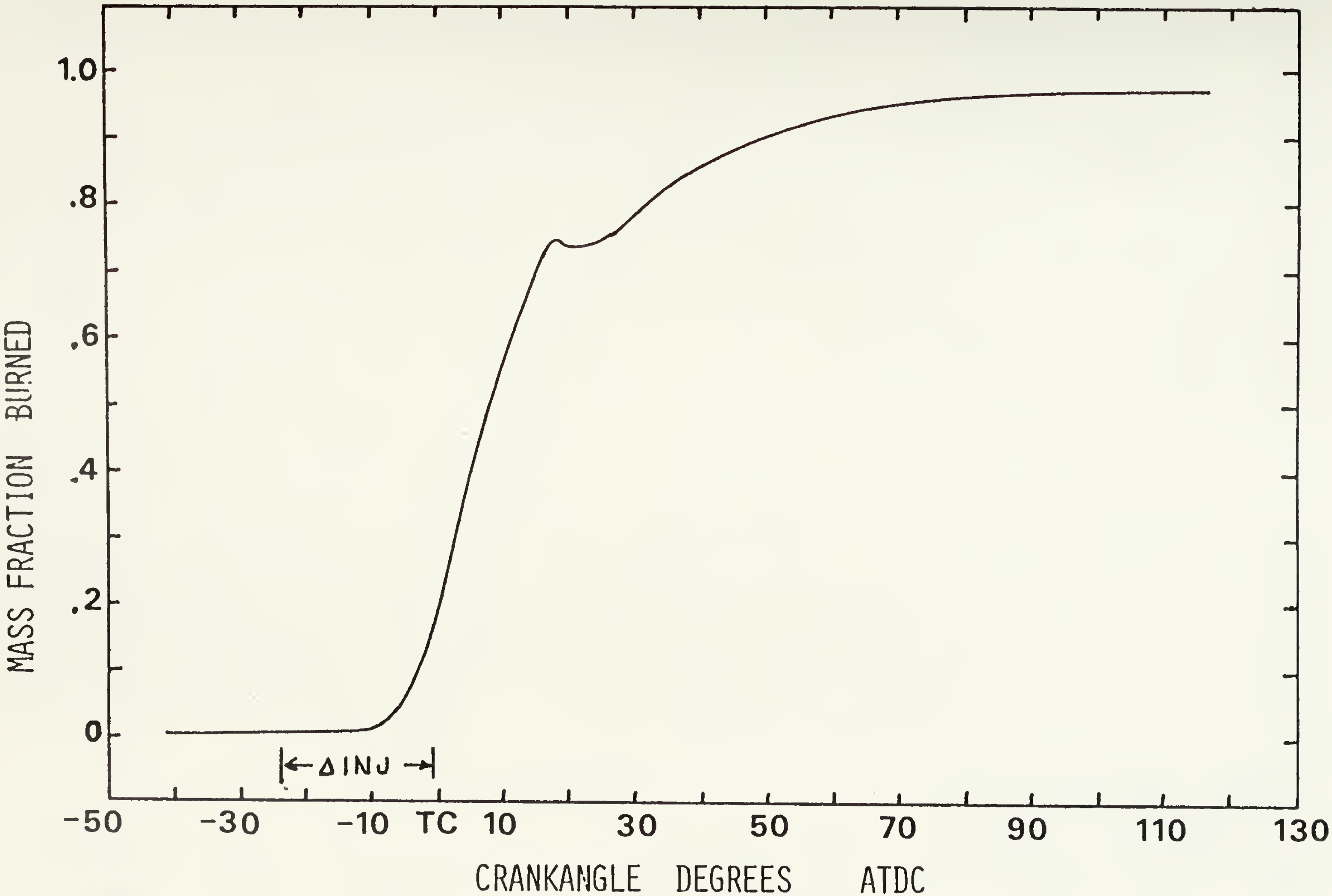


FIG. **59** FUEL MASS FRACTION BURNT VS CRANKANGLE FOR VARIABLE ϕ_B

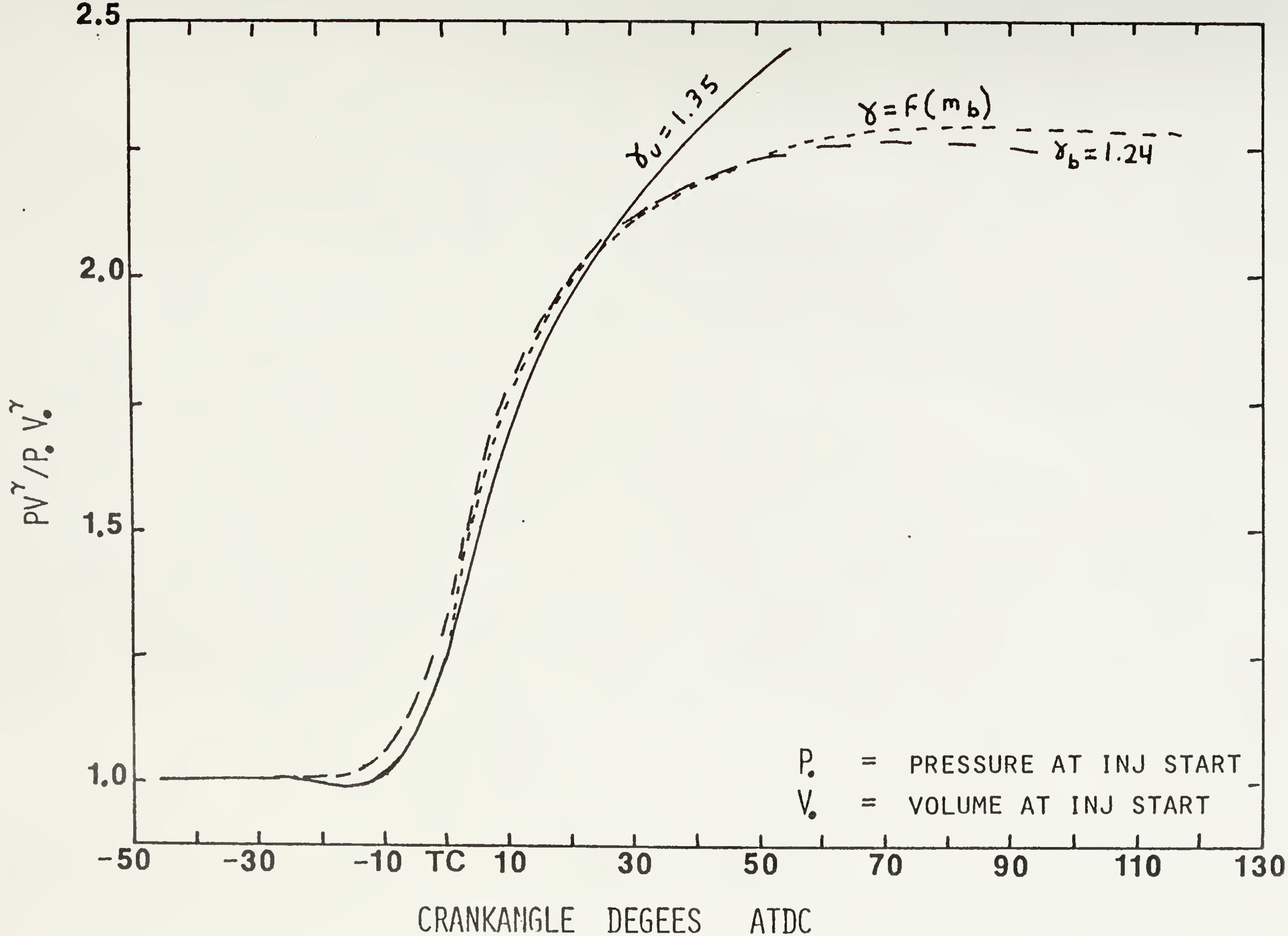


FIG. 60 PV^{γ} VS CRANKANGLE WITH BURNT AND UNBURNT GAMMA VALUES

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